Proceedings of the Gulf of Maine Ecosystem Dynamics

Scientific Symposium and Workshop

September 1996

CONVENED BY THE

Regional Association for Research on the Gulf of Maine

Regional Association for Research on the Gulf of Maine

The Regional Association for Research on the Gulf of Maine (RARGOM) was founded in 1991, based on the recognition that there was a need to stimulate, facilitate and coordinate scientific research focused on the Gulf of Maine as a natural system. The purpose of the Association is to foster quality scientific research on the Gulf of Maine through increased communication and collaboration among the region's institutions. The Association coordinates and helps to support meetings and workshops on issues of broad community interest that are most effectively undertaken by a consortium. The Association provides an independent and neutral forum for discussion and facilitation of Gulf of Maine research; advocates for regionally focused research programs at federal and state/provincial levels; and promotes awareness of scientific achievements, issues and linkages between science, management and the public.

RARGOM is an association of institutions, with members from both the United States and Canada. Membership is available in two categories. Full membership is offered to universities, research laboratories, and state and federal agencies with a strong commitment to research activities in the Gulf of Maine. Currently, this includes the Bigelow Laboratory for Ocean Sciences, Dartmouth College, Maine Department of Marine Resources, Massachusetts Institute of Technology, United States Environmental Protection Agency, United States National Marine Fisheries Service, University of Maine, University of Massachusetts at Boston, University of New Hampshire, and Woods Hole Oceanographic Institution. Associate membership is available to state agencies, and organizations who are interested in furthering research on the Gulf of Maine, but without a large group of active researchers working in the Gulf. Such organizations currently include the Canadian Department of Fisheries and Oceans, Cornell University, Huntsman Marine Science Centre, Island Institute, Maine Geological Society, Maine State Planning Office, National Undersea Research Center at the University of Connecticut, New England Aquarium, Stellwagen Bank National Marine Sanctuary, Texas A & M University, University of Massachusetts at Amherst, University of Massachusetts at Dartmouth, Wells National Estuarine Research Reserve. Each member institution designates an official representative and an alternate to serve on the policy board, but RARGOM welcomes broad participation in its discussions and committee work.

The planning effort and coordination for the conference that this volume documents has been contributed by RARGOM member institutions. We thank them for their continuing support of regional science.

Model predicted trajectories for 30 meter deep drifters, launched along various transects in the Gulf of Maine. The yellow circles indicate the "numerical launch locations"; while the white lines indicate their respective 120 day "model predicted trajectories".
The drifters are tracked in the annual mean circulation, as predicted by the Dartmouth Circulation Model. Note the tendency for cyclonic circulation around the perimeter of the Gulf of Maine and over Georges Basin as well as the anti-cyclonic circulation around Georges Bank and Browns Bank.

Topography image courtesy by Dr. Richard Signell, U.S. Geological Survey, Woods Hole, MA, USA

Drifter tracks courtesy of Dr. Christopher E. Naimie, Dartmouth College, Hanover, NH, USA.

Proceedings of the Gulf of Maine Ecosystem Dynamics

A Scientific Symposium and Workshop

16-19 September 1996
St. Andrews, New Brunswick

Edited by Gordon T. Wallace and Eugenia F. Braasch

Published by the
Regional Association for Research on the Gulf of Maine

RARGOM Report 97-1

"Given the human distaste for difficult decision-making, especially in the face of uncertainty, it is all too seductive to oversimplify our model of the world and assert that those disciplines do provide adequate basis for our decisions. That makes it easier for both the decision makers and those interest groups who bear the immediate consequences of those decisions. .... But it is essential that fisheries managers not be deluded by that false certainty."

"The resource and the industries which use the resources, will be much better served by a more humble, more scientifically curious approach. .... I have certainly found that being frank about the fact that we do not have the science to say that a given decision is based in definitive knowledge greatly agitates the regulated community and their attorneys. The alternative — taking stands based on an assertion of confidence — is antithetical to scientific discovery. It polarizes and entrenches, and decreases the possibility that the right questions will be asked or that new answers will be found. In short, it decreases the possibility of adaptation to new knowledge or to real change in the ecosystem within which we manage."

Robin Alden, Commissioner
Maine Department of Marine Resources

Gulf of Maine Ecosystem Dynamics

Table of Contents

Acknowledgments

The Gulf of Maine Ecosystem Dynamics Scientific Symposium and Workshop was an interdisciplinary program that was initiated and planned by the Regional Association for Research on the Gulf of Maine (RARGOM). The success of this effort was in large part due to Gordon Wallace, who served as Chair of the RARGOM policy board and also devoted countless additional time and effort to the conference, from its conception, through the program logistics, to the completion of this report. We also thank the institutional representatives to the RARGOM policy board who served as steering committee members and contributed additional time and expertise to planning and participating in this program.

The conference host organizations, Atlantic Salmon Federation, Huntsman Marine Science Centre and the St. Andrews Biological Station, provided local support and help during the meeting. The local committee included: John Allen (chair), John Andersen, Wendy Watson-Wright, David Aiken, Mic Burt, Blythe Chang, Fred Page, Jamie Steel, Brenda Waiwood, and David Wildish. We particularly thank John Allen (Huntsman Marine Science Centre) and Brenda Waiwood (Canadian Department of Fisheries and Oceans St. Andrews Biological Station) for their hospitality. We also thank the Algonquin Resort staff and facilities for accommodating the specific needs of our conference.

The overview and recommendations summarized in this report represent the achievements of the participants. Those who presented plenary talks, posters, and reports of their research all contributed generously to the outcomes of this event. Insights in this volume are gleaned from many disciplines and interests, and illustrate the range of issues and concerns that comprise our current regional picture of the Gulf of Maine ecosystem.

The following organizations contributed major financial support for the conference and these proceedings: Dartmouth College, Davis Family Foundation, Gulf of Maine Council on the Marine Environment, Gulf of Maine Regional Marine Research Program, Henry P. Kendall Foundation, University of Massachusetts at Boston Environmental Coastal and Ocean Sciences Program and Urban Harbors Institute. Additional funds were received from the Bigelow Laboratory for Ocean Sciences, the Canadian Department of Fisheries and Oceans, United States Environmental Protection Agency, United States Geological Survey, the United States NOAA National Marine Fisheries Service, Woods Hole Oceanographic Institution Rinehart Coastal Research Center, and the Woods Hole Oceanographic Institution Sea Grant Program. This assistance is greatly appreciated.

Gulf of Maine Council on the Marine Environment

Design consultation and production of this publication was provided by Jack L. Hall, of Art Services, in Hartland, Vermont.

Citation:
This report should be cited as:
Wallace, G. T. and E. F. Braasch, eds. *Proceedings of the Gulf of Maine Ecosystem Dynamics Scientific Symposium and Workshop.* RARGOM Report, 97-1. Hanover, NH: Regional Association for Research on the Gulf of Maine, 1997.

Scientific Steering Committee

Conference Chair
Gordon Wallace
Environmental Coastal and Ocean Sciences Program
University of Massachusetts
Boston Harbor Campus
100 Morrisey Blvd.
Boston, MA 02125 U.S.A.
wallace@umbsky.cc.umb.edu

David Aiken
St. Andrews Biological Station
Canadian Department of Fisheries and Oceans
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
aiken@sta.dfo.ca

John Allen
Huntsman Marine Science Centre
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
allenj@nbnet.nb.ca

David Brooks
Dept. of Oceanography
Texas A & M University
College Station, TX 77840 U.S.A.
dbrooks@cobscook.tamu.edu

Wendell Brown
Ocean Process Analysis Laboratory
University of New Hampshire
Morse Hall
Durham, NH 03824 U.S.A.
wsbrown@kelvin.unh.edu

Rockwell Geyer
Dept. of Applied Physics and Ocean Engineering
Woods Hole Oceanographic Institution
Bigelow 98 Water Street, MS #12
Woods Hole, MA 02543-1053 U.S.A.
rgeyer@whoi.edu

Donald Gordon
Bedford Institute of Oceanography
Canadian Department of Fisheries and Oceans
Marine Environmental Sciences Division
P.O. Box 1006 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2 Canada
gordond@mar.dfo-mpo.gc.ca

Lewis Incze
Bigelow Laboratory for Ocean Sciences
P.O. Box 475
McKown Point
West Boothbay Harbor, ME 04575-0475 U.S.A.
lincze@bigelow.org

Gregory Lough
Fishery Oceanography Investigation
Northeast Fisheries Science Center
Woods Hole Laboratory
U.S. National Marine Fisheries Service
166 Water Street
Woods Hole, MA 02543-1097 U.S.A.
glough@whsun1.wh.whoi.edu

Daniel Lynch
Thayer School of Engineering
Dartmouth College
Cummings Hall
Hanover, NH 03755 U.S.A.
d.r.lynch@dartmouth.edu

Steering Committee

Lawrence Mayer
Darling Marine Center
University of Maine
25 Clark's Cove Road
Walpole, ME 04573 U.S.A.
lmayer@maine.maine.edu

Judith Pederson
MIT Sea Grant Program
77 Massachusetts Ave. E38-300
Cambridge, MA 02139 U.S.A.
jpederso@mit.edu

Norman Rubinstein
Narragansett Marine Lab
U.S. Environmental Protection Agency
27 Tarzwell Drive
Narragansett, RI 02882 U.S.A.
nrubinstein@narvax.nar.epa.gov

Ronald Schlitz
Northeast Fisheries Science Center
Woods Hole Laboratory
U.S. National Marine Fisheries Service
166 Water Street
Woods Hole, MA 02543-1097 U.S.A.
rschlitz@whsun1.wh.whoi.edu

David Stevenson
Assessment and Statistics Division
Marine Sciences Laboratory
Maine Department of Marine Resources
P.O. Box 8
West Boothbay Harbor, ME 04575-0008 U.S.A.
mrdstev@state.me.us

Bruce Tripp
Rinehart Coastal Research Center
Woods Hole Oceanographic Institution
193 Oyster Pond Road, MS #2
Woods Hole, MA 02543-1525 U.S.A.
btripp@whoi.edu

Brenda Waiwood
St. Andrews Biological Station
Canadian Department of Fisheries and Oceans
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
bwaiwood@sta.dfo.ca

Robert Wall
Gulf of Maine Regional Marine Research Program
Center for Marine Studies
University of Maine
5715 Coburn Hall, Room 14
Orono, Maine 04469-5715 U.S.A.
robert_wall@voyager.umeres.maine.edu

Gulf of Maine Ecosystem Dynamics
A Scientific Symposium and Workshop
Prospectus

General Planning Considerations

In the time passing since the January 1991 workshop in Woods Hole there has been a significant increase in the amount of scientific research conducted in the Gulf of Maine, the results of which will enhance our knowledge of the functioning of the Gulf of Maine ecosystem. While research conducted as part of the Gulf of Maine Regional Marine Research Board's regional research program and NSF and NOAA's jointly sponsored GLOBEC program on Georges Bank ecosystem dynamics represent major new initiatives begun since the last workshop, significant contributions to research having a more a more local focus have also occurred. Most of these latter contributions, which often have regional implications as well, continue to be made by the Sea Grant Programs within the region, the Massachusetts Water Resources Authority, the United States Geological Survey's Atlantic Marine Branch at Woods Hole, the NOAA National Undersea Research Center at the University of Connecticut, the Massachusetts Bay and Casco Bay National Estuarine Programs, and other diverse federal (United States and Canadian) state and privately funded programs such as the ecosystem modeling project in Cobscook Bay.

Some of the goals outlined at the last symposium have received attention and others have not. This workshop, to be held in September 1996, is designed to provide a synthesis of progress made, reexamine old and establish new priorities, and provide a regional voice for the conduct of a well-designed course of research for the future. While the Woods Hole workshop allowed us to synthesize and review, the second is designed to build on results of recent research and reshape a research agenda within a regional context. This agenda should be directed towards conducting the innovative basic and applied research needed to solve practical problems of particular significance to the Gulf of Maine region. The mission of the workshop is to foster the exchange of ideas in the assessment of these critical needs, and perhaps more ambitiously, to challenge the scientific community at large to achieve some consensus in setting basic priorities for the future.

A Two Step Process

In an era of dwindling resources and diminishing public support (and understanding) of the contributions of basic research it is necessary to maintain an appropriate level of sensitivity to the need to demonstrate the achievements of past and ongoing research and, ultimately, to provide clear assessments of these benefits to society as a whole. To this end we view the conduct of the September workshop as a first step in a two step process. The first step is to clearly identify research accomplishments and identify (and justify) future research questions and priorities from a scientific perspective as described above. The second is to devise new methods of translating and incorporating the results of this research for use in making management and policy decisions.

This second step to be accomplished in a separate follow-up workshop to be held in the spring of 1997. In this workshop a smaller group of practicing scientists and managers will be asked explore new approaches in the integration of science and technical information in the management, policy, and regulatory processes needed to address region-wide issues affecting the environmental health of the Gulf of Maine and its resources. The workshop will focus on specific issues identified in the September workshop to be of mutual interest by both the management and scientific communities in the Gulf of Maine region.

The need for the second workshop is evidenced by the unforeseen consequences of well-intentioned policy and legislative actions to protect/ enhance/ restore environmental quality when based on limited and often inadequate scientific understanding of ecosystem function. The results of such actions can be costly to both society as a whole as well as to the ecosystem the actions are meant to protect. With few exceptions, members of both the scientific and management communities recognize that enhanced communication would be of mutual benefit. However, identification of appropriate mechanisms that result in consistent, truly meaningful integrated activities leading to practical, cost-effective, environmentally-sound decisions have yet to be identified, despite repeated pleas to do so (including that from the January 1991 workshop).

The results of the scientific workshop in September will identify priority scientific issues largely from the perspective of the scientific community. The identification of those issues raised by management and policy concerns where scientific understanding is limiting effective decision making will be the goal of the second workshop. Attempts to define innovative new approaches to integrated decision making processes that are satisfactory to the needs of both the management and scientific communities will be an important goal of this second workshop.

To establish a firm linkage between the two workshops, we are inviting leaders in the management and policy sector from both the U.S. and Canadian states and provinces bordering the Gulf of Maine as well as appropriate leaders from the federal sector in both countries to attend the St. Andrews workshop. They are being asked to provide the scientific community attending the workshop their perspective on what scientific information would be most useful to them in the solution of their problems. More specifically, we are inviting each of them to identify the three most pressing issues where additional scientific information would be most valuable.

There are several objectives of this approach:
- to provide the scientific community a current understanding of these issues,
- to make the scientific community aware of and consider the results of recent progress and its potential application to the understanding of these issues,
- and, while in the process of identifying new research needs from a largely scientific perspective in the working sessions, identify the subset of those priorities most relevant to these management issues.

The second workshop, ideally developed in conjunction with the scientific workshop, will focus on integrating the findings of the scientific workshop with contemporary management issues in the Gulf of Maine region. The specific format, timing and organizational aspects of this second workshop have not yet been decided but the planning process for this workshop will be initiated in the near future.

The general goals of the scientific workshop, plenary session themes and working group topics have been agreed upon. A brief outline of the workshop is presented below.

1. The title of the workshop will be "Gulf of Maine Ecosystem Dynamics Symposium and Workshop".
2. The goal of the workshop will be to produce the next generation of research priorities and scientific questions for the Gulf of Maine.
3. To accomplish this goal, recent scientific advances from research completed after the January, 1991 Gulf of Maine Scientific Workshop, will be presented. Included will be an assessment of the progress towards understanding the ecosystem(s) of the Gulf of Maine keeping in mind the goals stated in the January 1991 workshop. Presentation of these advances will take the form of plenary talks and poster sessions.

In addition to synthesizing advances in each of the topical areas identified below, plenary speakers are being asked to include a discussion of the role of modeling in each of the areas and to highlight key issues in both nearshore and offshore environments of the Gulf.

Poster sessions, which allow presentation of more detailed subject matter, will be conducted throughout the course of the meeting. We are anticipating publication of the plenary talks in full, and extended abstracts for the poster session presentations, as was the case in the January 1991 workshop.

4. The working group discussions will be structured to foster cross disciplinary examination of contemporary research concerns in the focus areas identified below. "Mini"-presentations, brief (less than 5 minute) presentations of individual research results by members of each working group will be allowed to stimulate and orient each working group's discussions. Each of the speakers is, however, expected to provide a more detailed synopsis of their research in the form of a poster. Model development and use will be a subject of discussion in all working groups.

Program Sessions

Evening Panel Discussion

Contemporary Management Issues Requiring Scientific Research

Invited Panelists:

Robin Alden, Commissioner, Maine Department of Marine Resources

William Ayer, New Brunswick Department of the Environment

Trudy Coxe, Secretary of the Executive Office of Environmental Affairs, Commonwealth of Massachusetts

John DeVillars, Region I Administrator, U.S. EPA

George Finney, Director, Environmental Conservation Branch, Atlantic Region, Environment Canada

William Hubbard, Chief, Environmental Branch, U.S. Army Corps of Engineers

Peter Partington, Regional Director, Fisheries Management, Department of Fisheries and Oceans

Andrew Rosenberg, U.S. National Marine Fisheries Service

Peter Underwood, Deputy Minister, Nova Scotia Department of Fisheries

Robert Varney, Commissioner, Environmental Services, State of New Hampshire

Moderator: Jerry Schubel, President, New England Aquarium

Plenary Sessions

The Influence of Circulation on Population Dynamics in the Nearshore and Offshore Environments of the Gulf of Maine

A. Circulation of the Gulf of Maine- Observations, Models and Biological Implications (Robert Beardsley).

This talk will provide a broad-scale view of the circulation of the Gulf of Maine, drawing from recent observational studies and numerical models. It should emphasize the advances in our understanding over the last five years and the limits to our understanding. Examples of biological implications of the circulation should be discussed, in coordination with the other talks.

B. Life-cycles of Organisms and the Annual Cycle of Circulation and Water Properties in the Gulf of Maine (Ted Durbin).

This talk will demonstrate our current understanding of life-histories of selected organisms (particularly copepods) in the Gulf of Maine and Georges Bank and show how they are coupled to or influenced by the seasonal variations in currents and water properties.

Influence of Vertical Transport and Exchange on Population Dynamics

A. Vertical Transport and its Influence on Nutrients, Benthic and Pelagic Communities (Peter Smith).

This talk will discuss recent advances in our quantitative understanding of vertical mixing, internal waves, and upwelling in the Gulf of Maine. It will explore the influence of these processes on nutrient transport and the implications on phytoplankton and higher trophic levels.

B. Small-Scale Physical-Biological Interactions (Lew Incze).

This talk will present new findings about small-scale interactions between flow and organisms that may have important implications on tropho-dynamics and modeling such as scales of turbulence, patchiness, influence of fronts, Langmuir cells, how Right Whales survive.

Biogeochemical Processes and Contaminant Inputs

A. Biogeochemical Cycling of Carbon and Nitrogen in the Gulf of Maine (David Townsend)

B. Sources, Transport and Fate of Contaminants in the Gulf of Maine (John Farrington)

These talks are to address the following questions. What is the current understanding of the biogeochemical cycling of carbon, nitrogen and selected contaminants in the Gulf of Maine? What are the primary sources? What is the relative importance of point and non-point sources? What are the temporal and spatial variabilities in distribution and fluxes of these elements? What are the dominant processes controlling this variability? How important is the coupling between the nearshore and offshore environments? To what extent do we know and understand the processes governing the flux of contaminants and nutrients from watersheds into the estuaries, nearshore and offshore regions of the Gulf of Maine?

Human-Induced Biological Changes in the Gulf of Maine

A. Physical Habitat Degradation and Resource Exploitation in the Gulf of Maine (Les Watling, Bob Steneck)

B. Biological Effects of Contaminant and Nutrient Inputs into the Gulf of Maine (Judy McDowell, Jack Kelly)

These talks will attempt to identify what human activities have demonstrably affected biological populations (at any phyletic level) and in the process, deal with the following topics. What and where are the imminent or ongoing problems most apparent to us, based on demonstrated biological change? What are the longer-range, sleeper problems that we might predict from knowledge of ongoing processes in the Gulf? Examples include toxic contamination, physical disruption (dredging, dragging), changes in nutrient and oxygen regimes, climate change-induced disruptions, new species introductions, and selective removal of species (fishing). Which habitats are likely most sensitive?

How do we detect impacts on biological populations, what kinds of non-biological measurements are useful, how do we quantify and express uncertainty in the detection process, and how do we avoid the chicken-little syndrome? What kinds of ecological models exist to predict the community effects that result directly and indirectly from human activity? Are small- or large-scale models more useful in assessing impacts?

What is the reversibility of these problems; are there historical perspectives to suggest the ability of communities to rebound? What are the likely rates of recovery? Do existing gradients of stressors in the Gulf provide predictive or testing opportunities, or is small-scale heterogeneity too great?

In approaching these questions, there must be cognizance that biological impacts can be perceived from two end-member perspectives. One is dictated by human values; for example, the public might have special fondness for some species in the ecosystem that has relatively little impact on overall ecosystem functioning. The other is one we might term a more objective assessment, in which only significant alterations to overall biomass or community structure are considered. Neither approach is the "right" one, but the two need to be separated in addressing the questions above.

Recent Advances and Problems in Fisheries Science (Mike Sinclair)

This talk will review advances in fisheries science in the Gulf of Maine nearshore and offshore regions during the last five years. What have we learned that has improved our ability to manage the fishery resources of the Gulf or that will enhance our ability to do a better job in the future? More specifically, what has been learned that has been or could be applied towards the identification and quantification of linkages between exploited and non-exploited species and between the living marine resources of the Gulf and their physical environment? What are the key scientific uncertainties that complicate the status quo stock assessment process and what can be done (or is being done) to improve the quality of the biological advice provided to fisheries managers?

To what extent can the failure to adequately manage fishery resources in the northwest Atlantic (e.g. cod) be blamed on poor science or inadequate information? Is there reason to believe that an ecosystem-based approach to fisheries science could provide a more useful basis for management than the currently applied single-species, population-dynamics models or could be used to complement current stock assessment procedures? Using the Gulf of Maine as a case study, what kind of an approach is called for and what kind of information would be needed to make it work? What kinds of research programs would be required to generate the necessary information? Are there examples of successful ecosystem-based management in other types of ecosystems (terrestrial, freshwater) or in other marine ecosystems from which we might learn how to proceed in designing a research and management strategy for the Gulf of Maine?

Ecosystem Modeling Assessment/Overview
(Eileen Hofmann and Job Baretta)

These talks will summarize developments toward a predictive ecosystem model for the Gulf of Maine since the first Gulf of Maine Scientific Workshop (January 1991), and evaluate future requirements and present limitations to the approach. The following questions will be addressed: What should be the goals and scope of ecosystem modeling for the Gulf of Maine? What is the time frame required to meet the goals? Can these goals be realistically achieved through a unified model? What are the present limitations in theory, data, and techniques to reach a predictive ecosystem model for the Gulf of Maine? Are there more advanced ecosystem models from other regions in the world that the scientists working in the Gulf of Maine can use to advantage?

Aquaculture
(Joe Brown)

In addition to the above plenary sessions an invited talk addressing the various issues concerning aquaculture in the Gulf of Maine will be presented in an evening session on the first day of the workshop.

Working Group Sessions

Working group sessions were identified to be consistent with and compliment plenary session topics. Because of the limited number of working group topics chosen, the large number of participants anticipated to attend the workshop, and the diversity of the problems to be addressed in each of the working groups, each of the large working groups will be divided into smaller working sub-groups. Each will focus on a subset of the issues identified under each working group topic. The chairs of each of the sub-groups will present the results of their deliberations to the larger work group. The chair of the larger working group will then be responsible for overall synthesis for presentation at a final plenary session and publication in the proceedings of the workshop.

Physical and Biological Coupling in the Gulf of Maine

This working group will document the progress over the last five years in our understanding of and ability to model the physical processes of the Gulf, and the biological processes that are closely tied to the physics.
Issues:

- Circulation of the Gulf of Maine- does Bigelow's cartoon need to be revised?
- Circulation model - can we trust them? Do they agree with data? Are they ready to be used as management tools (case study of Mass Bay)? What are the weak links?
- In Sinclair's (1992) "Overview of the biological oceanography of the Gulf of Maine", he declares that population dynamics are largely forced by physics and that food webs are relatively "uncoupled". If this is true, than is it easier or harder to predict populations using circulation based models, zooplankton vs. fish populations?
- Nutrient fluxes.
- Small-scale physical/biological transport processes.
- Seasonal variability of biological and physical processes.
- Red tides: what more do we need to know to predict them?

Land/Water Interface: Biogeochemical Processes and Cycles in the Gulf of Maine, Natural and Perturbed

Issues:

- To what extent do we know and understand the processes governing the flux of contaminants from watersheds into the estuaries, nearshore and offshore regions to the Gulf of Maine?
- What are the key processes controlling the transport and distribution of contaminants in the Gulf of Maine?
- What is the relative importance of non-point and point sources for contaminants of environmental concern?
- What are the critical factors to be considered in assessing the sensitivity of critical habitats in the nearshore zone to contaminant fluxes or other stressors?
- Are offshore areas significantly impacted by contaminants from any source?
- How well do we understand the carbon fluxes in the Gulf of Maine and the processes affecting them?
- Are there significant linkages between biogeochemi-

cal processes occurring in nearshore and offshore environments or can they be treated (modeled) as relatively independent systems? If not what are the linkages and their significance?

Human-Induced Biological Changes in the Gulf of Maine
Issues:
• What and where are the imminent or ongoing problems most apparent to us, based on demonstrated biological change? What are the longer-range, problems that we might predict from knowledge of ongoing processes in the Gulf?
• Which habitats are likely most sensitive? What criteria can we use to define "critical" habitats? Do we know where they are? To what level of detail do we need to know?
• To what extent can we treat habitats as independent entities? Does it make sense to separate them into estuarine, nearshore and offshore habitats or are the linkages between them too strong?
• How do we detect impacts on biological populations? What kinds of non-biological measurements are useful? How do we quantify and express uncertainty in the detection process and avoid the chicken-little syndrome?
• What are likely to be the dominant stressors? Do existing gradients of stressors in the Gulf provide predictive or testing opportunities, or is small-scale heterogeneity too great?
• What advances in ecosystem risk assessment have been made? What kinds of ecological models exist to predict the community effects that result directly and indirectly from human activity? Are small- or large-scale models more useful in assessing impacts?
• What is the reversibility of these problems; are there historical perspectives to suggest the ability of communities to rebound? What are the likely rates of recovery?

Fishery and Aquaculture Issues
Issues:
• What has been learned in the last five to ten years that has improved our ability to apply ecosystem-level information to understanding the dynamics of exploited resource populations in the Gulf of Maine region?
• In general, what scientific progress has been made in recent years that improves our ability to evaluate and predict the effects of fishing on the structure and function of marine ecosystems?
• Is there a valid scientific basis for applying ecosystem management principles and practices to fishery management in the Gulf of Maine? What alternatives are there and which ones should be pursued? What kinds of information would significantly contribute to an ecosystem approach to management? How should it be collected?
• What are the short and long-term scientific issues regarding the interaction between capture and culture fisheries and between aquaculture and the nearshore coastal environment?
• What are the short and long-term scientific issues that must be dealt with to make aquaculture a sustainable activity in the coastal environment?
• Is the enhancement of over-exploited wild stocks of fish and shellfish a realistic objective in the Gulf of Maine? What scientific issues must be addressed in order to answer this question?

Special Poster/Demonstration: Research Methods and Tools

In the evening of day two we will have a special poster/demonstration session to disseminate information and encourage the application of new approaches in the conduct of research in the Gulf of Maine. Included will be cross-disciplinary uses of modeling, satellite remote sensing, data systems and research platforms. Private, institutional and government organizations have been invited to display their products and information at the workshop.

Conference Agenda

Monday, September 16 — **Registration and Introduction to St. Andrews**

1:30-5:00 p.m.	**Registration and Check-in** organizers: RARGOM and St. Andrews Biological Station Staff — location: Lobby Lounge
1:30-3:00 p.m.	**Poster Sessions A & B Set-up** — location: Upper Casino
	Tour of St. Andrews — Open House at host institutions **St. Andrews Biological Station** **Huntsman Marine Science Centre** **Atlantic Salmon Federation** St. Andrews local committee / organizers: John Allen (chair), John Anderson, Wendy Watson-Wright, Dave Aiken, Mic Burt, Blythe Chang, Fred Page, Jamie Steel, Brenda Waiwood (coordinator), Dave Wildish
3:00-5:00 p.m.	**Poster Session A: Physical and Biological Coupling & Fisheries and Aquaculture** — location: Upper Casino
5:00-6:15 p.m.	social hour at Upper Casino
6:15 - 7:15 p.m.	dinner buffet in Passamaquoddy Dining Room
7:15 - 7:30	**Welcoming Remarks** Gordon Wallace and St. Andrews hosts
7:30-9:00 p.m.	**Special Panel Discussion: Contemporary Management Issues Requiring Scientific Research** panel discussion: Jerry Schubel (moderator), Robin Alden, William Ayer, Peg Brady, Philip Colarusso, George Finney, Bill Hubbard, Peter Partington, John Rittgers, Chris Simmers — location: New Brunswick Room

Tuesday, September 17 — **Plenary sessions**

7:00-8:15 a.m.	breakfast buffet in Passamaquoddy Room
8:30-9:30 a.m.	**Influence of Circulation on Population Dynamics in the Nearshore and Offshore Environments of the Gulf of Maine** A. Circulation of the Gulf of Maine - Robert Beardsley B. Life cycles of Organisms and the Annual Cycle of Circulation and Water Properties in the Gulf of Maine - Edward Durbin — location: New Brunswick Room
9:30-10:30 a.m.	**Influence of Vertical Transport and Exchange on Population Dynamics** A. Vertical Transport and its Influence on Nutrients, Benthic and Pelagic Communities - Peter Smith B. Small Scale Physical-Biological Interactions - Lew Incze — location: New Brunswick Room
10:30-10:45 a.m.	coffee break in New Brunswick Foyer
10:45-11:45 a.m.	**Biogeochemical Processes and Contaminant Inputs** A. Biogeochemical Cycling of Carbon and Nitrogen in the Gulf of Maine - David Townsend B. Sources, Transport and Fate of Contaminants in the Gulf of Maine - John Farrington — location: New Brunswick Room
12:00-1:00 p.m.	lunch buffet in Passamaquoddy Room
1:00-2:30 p.m.	**Human-Induced Biological Changes - Important Stressors** A. Physical Habitat Degradation and Resource Exploitation - Les Watling and Bob Steneck B. Biological Effects of Nutrient and Contaminant Inputs - Jack Kelly and Judy McDowell — location: New Brunswick Room
2:30-3:15 p.m.	**Recent Advances and Challenges in Fisheries Science** speaker: Michael Sinclair — location: New Brunswick Room
3:15-3:30 p.m.	coffee break in New Brunswick Foyer
3:30-4:30 p.m.	**Ecosystem Modeling Assessment/Overview** A. Goals and Scope of Ecosystem Modeling - Eileen Hofmann B. Advanced Ecosystem Models in Other Regions in the World - Job Baretta — location: New Brunswick Room
4:30-5:00	**Open Discussion**
5:00-7:00 p.m.	**Poster Session B: Land Water Interface & Human-Induced Biological Changes** and social hour — location: Upper Casino
7:00 - 8:00 p.m.	salmon dinner in Passamaquoddy Dining Room
8:00-9:00 p.m.	**Special Topic: Aquaculture in the Gulf of Maine** speaker: Joe Brown — location: New Brunswick Room

Wednesday, September 18 — **Working Group sessions**

7:00-8:15 a.m.	breakfast buffet in Passamaquoddy Room
8:15-8:30 a.m.	**Charge to the Working Groups** speaker: Gordon Wallace — location: New Brunswick Room
8:30-10:00 a.m.	**Recent Research Results - 5 Minute Mini Presentation Sessions** location: New Brunswick Room
	Physical and Biological Coupling in the Gulf of Maine Presenters: David Brooks, James Churchill, Edward Durbin, Rocky Geyer, Charles Hannah
	Land /Water Interface: Biogeochemical Cycles, Natural and Perturbed Presenters: Michael Bothner, Robert Chen, Ted Loder, Cynthia Pilskaln
	Fishery and Aquaculture Issues Presenters: Ted Ames, Lew Incze, Rodney Rountree, Daniel Schick, Susan Waddy
	Human-Induced Biological Changes Presenters: Michael Connor, Mark Chandler, Michael Moore, Page Valentine
10:00-10:30 a.m.	coffee break in New Brunswick Foyer
10:30-12:00	**Working Group Sessions**
	Physical and Biological Coupling in the Gulf of Maine working group chair: Robert Beardsley subgroup discussion leaders: Rockwell Geyer, James Churchill, Edward Durbin, Lewis Incze rapporteurs: — location: New Brunswick Room
	Land /Water Interface: Biogeochemical Cycles, Natural and Perturbed working group chair: Donald Gordon subgroup discussion leaders: Theodore Loder, Philip Yeats, Bruce Tripp rapporteurs: Norbert Jaworski, Heather Benway, Marilyn Buchholtz ten Brink — location: Upper Casino and Lower Casino Chamcook Room
	Fishery and Aquaculture Issues working group chair: David Stevenson subgroup discussion leaders: David Stevenson, Ken Waiwood rapporteurs: Daniel Schick, Blythe Chang — location: Huntsman Marine Science Centre
	Human-Induced Biological Changes working group chair: Judith Pederson subgroup discussion leaders: Robert Buchsbaum, William Hubbard rapporteurs: Jim Shine, Laura Mucklow, Nick Houtman — location: Fundy Room and St. Andrews Room
12:15-1:00 p.m.	lunch in Passamaquoddy Room
1:30 -3:00 p.m.	**Working Group Sessions continued**
3:00-3:15 p.m.	coffee break

3:15-5:00 p.m.	**Working Group Sessions continued**
5:00-7:00 p.m.	**Special Poster Demonstration: Research Methods and Tools** and social hour
7:00 - 8:00 p.m.	chicken dinner in Passamaquoddy Dining Room
8:00-9:00 p.m.	**Special Poster Demonstration: Research Methods and Tools** Cross Disciplinary uses of modeling, satellite remote sensing, data systems, research platforms — location: Upper Casino

Thursday, September 19 — **Summary sessions**

7:00-8:15 a.m.	breakfast buffet in Passamaquoddy Room
8:30-9:00 a.m.	**Physical and Biological Coupling in the Gulf of Maine** working group chair: Robert Beardsley — location: New Brunswick Room
9:00-9:30 a.m.	**Land /Water Interface: Biogeochemical Cycles, Natural and Perturbed** working group chair: Donald Gordon
9:30-10:00 a.m.	**Fishery and Aquaculture Issues** working group chair: David Stevenson
10:00-10:30 a.m.	**Human-Induced Biological Changes** working group chair: Judith Pederson
10:30-10:45 a.m.	coffee break — location: Passamaquoddy Room
10:45-1:30 p.m.	**Synthesis Remarks by John Farrington** Conference evaluation — location: lunch in Passamaquoddy Room
1:30-3:00 p.m.	checkout for participants at Algonquin
1:30-5:00 p.m.	**Executive Summary & Report Planning Session** by steering committee

Executive Summary

Gordon T. Wallace
University of Massachusetts at Boston

The Gulf of Maine Ecosystem Dynamics Scientific Symposium and Workshop held in St. Andrews, New Brunswick, Canada, provided the first region-wide opportunity to synthesize and review advances in the scientific understanding of the Gulf of Maine ecosystem since the Gulf of Maine Scientific Workshop was held in Woods Hole, Massachusetts in January of 1991. Of particular value was the opportunity to share recent research results and perspectives between Canadian and U.S. scientists and managers having vital interests in the shared resources of the Gulf of Maine. Underlying themes in the Symposium were ecosystem modeling and consideration and recognition of the importance of transboundary linkages between terrestrial (air- and watershed) and adjacent marine ecosystems. The meeting opened with a series of presentations from a panel of Canadian and United States federal and regional environmental managers from the Gulf of Maine region. Each was asked to present the top three issues identified by the agencies and/or regions they represented that required additional scientific information to assist in decision making and policy development.

Following the management panel, invited plenary talks were presented that focused on five areas: 1) physical-biological coupling in the Gulf of Maine with special emphasis on the influence of circulation on population dynamics and the influence of vertical transport and exchange on biological processes, 2) biogeochemical processes and contaminant inputs, 3) human impacts on biological populations, 4) recent advances in fisheries science and 5) an overview and assessment of recent progress in ecosystem modeling. A special invited talk was given on issues related to the rapidly developing role of aquaculture in the Gulf of Maine region.

Working groups in four areas closely paralleling the above themes were convened to identify new research directions in the Gulf of Maine. All working groups were to include consideration of the role of ecosystem modeling in their deliberations. The working group sessions were preceded by mini-presentations of a subset of research reported from the poster session, which were used to stimulate deliberations in the working groups.

Finally, a joint management-science panel discussion concluded the program, the purpose of which was to identify a subset of research topics of common interest to both the management and science communities. Identification of these topics was based on a synthesis of the results of the discussion of issues raised in the initial management panel, the results of recent scientific research presented in the Symposium, and the working group discussions. These issues served as the focal points of a subsequent management-science workshop planned as a follow-up to the St. Andrews meeting. The purpose of the second workshop, held in June 1997, was to explore and develop new innovative processes to implement better cooperation and communication between managers and scientists in the Region. The result of this workshop, which provides specific recommendations to achieve this goal, is appended to these proceedings.

Management Panel Presentations and Discussion

Scientific issues surrounding fisheries management were frequently mentioned as a major area of concern. Of particular interest was the development of an ecosystem, rather than single species, perspective in the support of fisheries management. Peter Partington (Department of Fisheries and Ocean Canada), George Finney (Environment Canada, Atlantic Region), Robin Alden (Maine Department of Marine Resources) and William Ayer (New Brunswick Department of Environment) all identified the need to consider and develop a better understanding of ecosystem dynamics including such elements as linkages with physical, biological and chemical processes, species inter-dependence, life history and behavioral information, and habitat utilization and change. John Rittgers (NOAA National Marine Fisheries Service) argued for the need to build on existing data in the synthesis and assessment of anthropogenic effects on coastal ecosystems. He pointed out that parallel socio-economic analyses are needed to support unpopular management decisions where long-term benefits are anticipated at the expense of short-term losses. Alden emphasized the need for improvements in institutional structures to promote "stewardship, enhancement and aquaculture" as well as the need to better define appropriate management units that recognize recent advances in scientific information in fishery management.

A number of managers focused on issues related to contaminated sediments. Peg Brady (Massachusetts Office of Coastal Zone Management), William Hubbard (United States Army Corps of Engineers) and Philip Colarusso (United States Environmental Protection Agency) all indicated that scientific issues surrounding the disposal and containment of contaminated sediments and habitat restoration are of high priority. Uncertainties concerning watershed processes and their effects on habitat at the land-sea interface were also recognized and reflect the growing awareness of the coupling between land-based activities and coastal ecosystem dynamics. Additional knowledge concerning the releases of a wide variety of inorganic and organic contaminants of potential concern within the watersheds and their transport to the Gulf of Maine, and assessment of the alteration and destruction of habitat by modification of the temporal scale and magnitude of freshwater inputs by dams and other structures were also identified as important.

When asked to prioritize the list of issues identified that require additional scientific information, the managers present most frequently mentioned the following:

- Quantitative, watershed-based, assessment of the cumulative impacts of point and non-point sources of contaminants, especially of nutrients, on coastal resources
- The need for a better understanding of the life histories, behavior, food and habitat requirements of different developmental stages of fish and shellfish

Issues mentioned less frequently were:

- Identification and characterization of the critical fisheries management "unit"
- Characterization of the driving forces of change on the Gulf of Maine ecosystem

Members of the scientific community present, when asked for their input, rated the need to establish and sustain a long-term environmental monitoring program, linked to the development and use of appropriate ecosystem models, as a high priority. Linkage of long-term monitoring to long-term modeling efforts was considered a critical need in the development and refinement of forecasting capabilities. Success of both the monitoring and modeling efforts was also considered to be interdependent and require a well-coordinated, long-term commitment of resources. There was general agreement that the design of both the monitoring and modeling programs must be sensitive to, and meet the needs of, all user groups in the region.

Plenary Talks

Physical-Biological Coupling

Beardsley et al. reviewed recent field and modeling activities in the Gulf of Maine. The coupling of these efforts with the finer resolution spatial and temporal scale measurements being made should enable an enhanced understanding of the complex circulation dynamics of the Gulf. The evolving picture of the Gulf is one influenced by both large-scale (e.g., the buoyancy-driven shelf/slope coastal current extending from the Labrador Sea to Cape Hatteras, Gulf Stream Rings) as well as more local (e.g., topography, river input, wind) processes. While most of the research underway is regional in scope, more localized efforts (in Massachusetts Bay and a number of Maine estuaries) are in progress or have been recently completed. No fewer than thirteen modeling efforts were identified, ranging in scope from simulation of the new Massachusetts

Water Resources Authority's outfall plume characteristics to further development of Gulf-wide circulation models. Significant advances in the development of regional electronic distributed databases and communication capabilities have, to some extent, facilitated the use and sharing of the research products, at least within the scientific community.

Ted Durbin presented a synthesis of recent research and historical data on the distributions and coupling of zooplankton population dynamics with physical processes in the Gulf of Maine. He identified four provinces: estuarine, coastal well-mixed, central, and shallow offshore banks, each of which support distinct zooplankton assemblages. Temporal and spatial differences in populations and life stages in each of these regions were linked to both local and large-scale physical processes. Peter Smith provided a synthesis of recent field and modeling exercises in examining the influence of vertical mixing in the Gulf. Mechanisms leading to interannual differences in seasonal vertical mixing in the three major basins and the formation of Maine Intermediate Water, tidally-induced and topographically modified upwelling off Cape Sable, and mechanisms driving vertical exchange on Georges Bank and the Scotia Shelf were all addressed. He also presented the results of a number of process and comprehensive models developed for the Gulf and concludes with an evaluation of research needs to further understand and describe vertical exchange in the Gulf. Smith argued that future efforts should rely on a "blended approach" integrating both model and field efforts that could help define the effect of interannual, and eventually long-term (climate-change scale), changes on vertical exchange processes. He identified the effect of high frequency events (storm-induced) on vertical mixing in the western Gulf, and wind and tidally-driven processes, especially in areas where vertical mixing strongly influences biological productivity, to be of particular interest.

Lew Incze discussed small-scale turbulence and its importance, realized and potential, on biological processes. He provided a concise summary of the theory and experimental evidence supporting the importance of small-scale turbulence on zooplankton feeding rates, especially for larval fish. While careful to illustrate the complexity in interpreting both field and laboratory work on the role of turbulence on feeding and other behavioral aspects of plankton dynamics, and their coupling to higher trophic levels, Incze pointed out the opportunities provided by the heterogeneous environment of the Gulf of Maine and the ongoing field and modeling efforts to advance this rapidly evolving field.

The series of presentations in the area of physical-biological coupling illustrated the need to consider temporal scales extending from seconds to centuries and spatial scales from mm to thousands of km to adequately resolve the dynamic coupling of physical and biological processes known to be important in the Gulf. Favorable comparison of model-predicted vertical fluxes of nutrients with that needed to support observed primary production for some regions of the Gulf is but one area where the utility and success of both process and comprehensive models seem to be making substantial contributions to our understanding of the ecosystem of the Gulf. The continued evolution of such modeling efforts, and especially their extension to interdisciplinary use, will be a valuable tool in advancing our knowledge of the many complex processes that dictate the overall ecosystem dynamics of the Gulf of Maine.

Biogeochemical Processes and Contaminant Inputs

Knowledge of the biogeochemical processes controlling the cycling of carbon and nitrogen is of fundamental importance in understanding ecosystem dynamics in the Gulf. David Townsend revisited earlier assessments of the annual Gulf-wide cycling of nitrogen using recently obtained data and concluded that either the Gulf has an unusually low "f"- ratio (the fraction of "new" inorganic nitrogen utilized to support primary production relative to the sum of both new and recycled (old) inorganic nitrogen-based primary production), or that there is a substantial vertical flux of new nitrogen entering Maine surface waters that is currently not well documented. Townsend presented evidence that the "new" nitrogen supply may be driven by intense nitrification immediately below the surface mixed layer, but cautioned that there are still large uncertainties regarding advective inputs of nitrogen into Maine surface waters. Improved estimates of both vertical and horizontal fluxes of inorganic nitrogen will be needed to further resolve the annual nitrogen cycle of the Gulf. Inorganic carbon cycling and transfer of carbon to higher trophic levels were identified as important research needs that could lead to a better understanding of the cycling of carbon in the Gulf.

In a brief overview of the sources, transport and fate of chemicals of environmental concern, John Farrington noted both the increase in general knowledge regarding the processes affecting the behavior of such substances as well as advances in site-specific knowledge of inventories, rates and processes based on recent studies in the Gulf. He observed that evaluation of non-point sources has taken on added importance as control of point-source discharges has improved. Recent compilations and analyses of existing data confirmed that sediment concentrations of contaminants of environmental concern are generally elevated in nearshore regions. There is also a general increase in concentrations in both sediments and organisms from north to south, paralleling changes in population densities in the coastal zone of the Gulf. Advances in understanding the processes controlling these distributions should allow similar advances in modeling efforts to better predict the fate and bioavailability of contaminants of environmental concern introduced into the Gulf from both point and non-point sources. This information should stimulate and support the evolution of appropriate interdisciplinary models to assess both ecosystem and human health consequences of such discharges. Farrington identified four other areas of importance concerning chemicals of environmental concern in the Gulf: 1) the need to improve source strength estimates, 2) assessment of the bioavailability and release of chemicals from contaminated sediments, 3) exploitation of new technologies to study the biogeochemistry of offshore regions of the Gulf and 4) exploitation of opportunities afforded by the reduction in, and relocation of, point-source contaminant loading in Boston Harbor and Massachusetts Bay.

Human Impacts on Biological Populations - Important Stressors

Les Watling examined anthropogenic alterations of habitat by physical mechanisms and concluded that the use of mobile fishing gear in the Gulf is by far the most damaging wide-spread human-induced disturbance of the benthic environment on a Gulf-wide basis. Alterations of deep-water habitats are of particular concern as they would generally be free from storm-induced natural perturbations. These habitats ordinarily represent stable and complex bottom environments supporting diverse benthic communities. In addition to documenting loss of organisms caused by mobile fishing gear in both hard and soft bottom substrates, Watling suggested that the loss of structural complexity of benthic habitat may ultimately result in lower biodiversity. He speculated on the effects of such disturbance on critical benthic processes and concluded that the fisheries management community should view the influence of mobile fishing gear from the much broader perspective of conservation of biodiversity, rather than simply as an issue of gear conflict.

Robert Steneck focused primarily on human-induced changes in the nearshore ecosystem resulting from increased fishing pressure, first on large predatory groundfish that has led to their "functional absence" from large regions in the Gulf, and more recently on lower trophic levels (urchins, lobsters). Steneck argued that this pressure, exerted primarily on higher trophic level predators, can result in profound and complex changes in ecosystem dynamics at all trophic levels. Both Steneck and Watling presented strong cases that the effects of fishing-related impacts have and will continue to exert significant perturbations on the ecosystem of the Gulf in both nearshore and offshore habitats, and that these ecosystem-level perturbations must be considered in management decisions.

John Kelly used data from a number of coastal embayments in the Gulf of Maine as well as the extensive database for Boston Harbor/Massachusetts and Cape Cod Bays to evaluate embayment sensitivity to nutrient enrichment. More importantly he presented an overview of the principal variables to be considered in making such an evaluation and the need to consider the temporal and spatial framework in the assessment process. He found little evidence that wide-scale nutrient enrichment is of great concern due to the typically well-flushed nature and short water residence times in the coastal embayments of the Gulf. In fact most of the nutrient input to the estuaries examined could be attributed to exchange with offshore waters rather than watershed inputs. Nevertheless Kelly indicated that site-specific evaluation of critical variables over appropriate time scales is needed before management decisions regarding nutrient loadings can be made for any given embayment.

In a general overview of the distribution and observed biological effects of contaminants in the Gulf of Maine, Judith McDowell cited a number of recent observations of the physiological state of shellfish and bottom-dwelling fish in the coastal areas of the Gulf. These observations further support the existence of the detrimental effects linked to the presence of lipophilic contaminants, such as polychlorinated and halogenated aromatic hydrocarbons. Even in areas away from severe contamination by these compounds, other compounds such as herbicides or dioxins may be significant and affect soft-shell clam populations. McDowell noted the need for further elucidation of cause and effect relationships between contaminant concentrations in tissues and biological effect for many of the contaminants known to be entering the Gulf. In assessing monitoring needs she pointed out that the temporal and spatial resolution of existing monitoring programs is insufficient to define distributions, let alone changes in distributions, of contaminants of environmental concern in the Gulf. Existing monitoring programs also cannot support meaningful interpretation of the relationship of contaminant distributions to ecological or human health consequences. Source identification, biogeochemical cycling, and assessment of changes in physiological condition or other biological changes in populations of organisms that occur in areas with strong gradients in potential contaminant exposures were among the needs identified for future work.

Recent Advances and Problems in Fisheries Science

Michael Sinclair used a case study of changing cod stocks in the Scotian Shelf/Gulf of Maine area to explore both environmental and management issues affecting such changes. The collapse of cod stocks on the Scotian Shelf was largely attributed to: 1) the setting of total allowable catches that exceeded recommendations based on scientific advice, 2) quotas established upon this scientific advice were, in most cases, well above the 20% annual removal of cod biomass recommended as the limit needed to maximize yield per recruit, and 3) actual landings exceeded the already excessive total allowable catches. More recent analysis suggested that the loss of spawning populations caused by several environmental factors might have also contributed to the collapse. These factors were: 1) concentrated fishing efforts in spawning areas between 1981 and 1986, 2) the presence of cooler than normal summer bottom water temperatures in recent years that restricting favorable habitat and may have therefore increased "catchability", and 3) increased predation of juvenile cod by exponentially increasing Grey seal populations. With this new understanding of the causes of the collapse, Sinclair argued that proper implementation of a number of management activities should allow substantial improvement in the single-species management approach being used. Uncertainties remain, however, regarding the minimum spawning biomass necessary to support adequate recruitment, the effects of environmental variables (such as the above mentioned change in bottom temperatures and increased natural mortalities) and recovery times of depleted stocks, all of which complicate the formulation of appropriate management strategies. Finally, Sinclair presented his perspective contrasting the currently implemented single-species management perspective with that of an ecosystem-management perspective in which food-chain dynamics are considered. He argued that, while environmental variables, such as changes in temperature and physical circulation do influence population abundances, the abundance of top predators, such as cod are largely uncoupled from food-chain interactions. For this reason he concluded that single-species management may be achievable by control of fishing effort rather than taking the much more complex and currently untenable approach required of ecosystem management.

Ecosystem Modeling

As noted earlier, ecosystem modeling was one of the unifying themes of the Symposium, both as a framework for conducting research and as a means of communicating results. In the last five years there has been a tremendous growth in the development and use of circulation models in the Gulf of Maine, although coupling of biological and chemical processes into these models is at an early stage. Eileen Hofmann reviewed the different approaches to ecosystem modeling as well as the current status of such models for the Gulf of Maine. She indicated that elements limiting the successful development of models are inadequate resolution of the temporal and spatial domain of both the appropriate physical and especially biological processes, the failure to design physical circulation models that can be easily coupled with biological models, and the lack of adequately resolved biological models that include the necessary conceptual framework and rates of key dynamical processes. She argued that development of a predictive ecosystem model for the Gulf of Maine must begin with establishment of a yet to be realized over-arching conceptual model of the system followed by identification and acquisition of the necessary data on biological processes and rates. Successful integration of such data into physical circulation models require that the physical models be developed in a truly interdisciplinary sense that recognizes the structural, temporal and spatial scale requirements of the biological processes being incorporated into the model.

Baretta described the European Regional Seas Ecosystem Model (ERSEM) developed as part of the Marine Science and Technology Program of the European Union, which is supporting a multi-institutional and multi-disciplinary effort to describe the ecosystem dynamics of the North Sea. The model framework had been clearly defined at the outset and provided the necessary definition to allow the design and integration of numerous submodels into the model. Using this still-evolving series of benthic and pelagic submodels, coupled to a simplified multibox exchange model (driven by the output of various hydrodynamic/transport models), the model has been able to resolve observed climatological variations in nutrients, oxygen and organic carbon. Higher trophic level dynamics are not resolved as the model relies on functional grouping of organisms rather than detailed structural hierarchies within and between groupings. Model agreement between observed and predicted changes over an annual cycle was reasonable. The model has also been used to examine the sensitivity of North Sea annual production rates to reduction in river input of nutrients. Predicted reductions in primary production rates, even in coastal "boxes" directly receiving river discharge, were much less (by as much as 50%) than corresponding hypothetical reductions in nutrient loading. Depending on the nature of the as yet to be defined "overall over-arching conceptual model" chosen for the Gulf of Maine system, which both Hofmann and Baretta agree is the critically needed first step, an approach similar to ERSEM may be applicable to the Gulf of Maine ecosystem.

Aquaculture in the Gulf of Maine

Aquaculture, one of the most rapidly growing "fisheries" in the world, and worth almost $150 million (U.S.) in 1995, is becoming an increasingly important activity in the Gulf of Maine. Joe Brown reviewed the current status and problems facing the aquaculture industry in the region. Based on his data, about 15% of North America's aquaculture revenues are derived from Gulf of Maine sources. The major species being aquacultured are the Atlantic salmon, steelhead, trout and Northern Quahog. The major fraction (94%) of the income from aquaculture in the Gulf of Maine region is derived from activities in New Brunswick (Bay of Fundy) and in Maine. Development of new species for aquaculture, as well as expansion of programs for the enhancement of existing fishery stocks, represent substantial opportunities for expansion of aquaculture in the Gulf of Maine. Enhancement could be accomplished by: 1) release of eggs and larvae at critical times and in appropriate habitat, 2) the release of cultured juvenile fish, or 3) by the capture of juvenile cod from the wild followed by enhanced growth in pens for several years and their return to the wild. Brown identified government regulation, predation, and availability of financial capital as major obstacles hindering the rapid growth of aquaculture. He felt that environmental impacts associated with aquaculture, while not trivial, could be largely controlled or mitigated with appropriate environmental stewardship by all parties involved. He concluded that close international cooperation between managers and scientists and active participation by all stakeholders to solve environmental and user-conflict issues associated with aquaculture efforts in the Gulf of Maine will be required.

Working Group Reports

Physical-Biological Coupling

Three discussion areas were identified by the Physical/Biological Coupling Working Group: 1) estuarine/nearshore/Gulf/slope exchange, 2) benthic-pelagic coupling and life cycles and 3) physical processes. The scientific issues considered by the working group and specific research topics identified as part of their deliberations were summarized in two tables. There was considerable interest in focusing on various aspects of the coastal current including along-current transport, across-shelf exchanges in the nearshore zone, and dynamics within the current and at frontal boundaries. These processes strongly influence both biological processes and the distribution and transport of organisms and chemicals in the Gulf. As such they influence the retention and/or transport of contaminants in the Gulf and establish biological habitats distinctly different from those offshore. Benthic-pelagic coupling was identified as a key area, partly in response to the recent evidence of extensive disturbance of benthic habitat by fishing activities, particularly in the offshore areas of the Gulf. The influence of internal waves on resuspension and transport of sediments and on vertical mixing processes in the vicinity of the productive coastal front was also identified as a potentially fruitful area for research. In nearshore areas, an increased understanding of interactions between benthic and planktonic organisms was high densities of benthic animals, coupled with strong tidal influences, tend to amplify such interactions. In addition, the influence of benthic remobilization of nutrients, known to be important in other coastal ecosystems, was suggested as an area where additional information could be useful. With respect to life-cycles and physical processes, focus on the dynamics of cod ecology and harmful algal blooms were identified as topics of continued interest. Both were considered as logical extensions of ongoing work that could be integrated with other identified issues (estuarine and coastal-current dynamics) and be approached jointly by Canadian - U.S. cooperative efforts.

Land/Water Interface: Biogeochemical Cycles, Natural and Perturbed

Three subgroups were formed, one to discuss issues surrounding the cycling and dynamics of carbon, nitrogen and phosphorus while the other two sub-groups both dealt with issues related to inorganic and organic contaminants in the Gulf. In reviewing the current status of knowledge, it was generally agreed that knowledge of the nutrient dynamics in the Gulf of Maine has been improved over the last five years, especially when considered in light of advances in our understanding of the physical circulation of the Gulf. While the major input of nutrients enters the Gulf by advective transport of water from the north, questions regarding the magnitude and temporal and spatial dynamics of watershed-related, anthropogenically enhanced introduction of nutrients into nearshore regions of the Gulf were raised. The impacts of changing populations and land-use patterns, shifts in nutrient ratios in freshwater discharged to the Gulf, the episodic pulses of nutrients introduced during periods of high runoff, and modification of runoff events by man-made structures (dams, causeways etc.) were among the areas identified as requiring further research. On a larger scale it was noted that establishing the mass balance for nutrients in the Gulf remains an elusive target, as does adequate understanding of the internal cycling and transport of nutrients, information needed in the construct of working large-scale ecosystem model(s) for the Gulf. Both *in situ* (instrumented moored arrays) and external (e.g., satellites) sensors were identified as methods which, when properly ground-truthed, could markedly expand current data acquisition efforts in support of development of these models.

Sub-groups focused on contaminants noted that advances in our knowledge of the magnitude and composition of point (primarily in the form of sewage effluent) and non-point (primarily via atmospheric, runoff, in-place contaminated sediments and groundwater inputs) has increased but is far from complete. Additional information on the variables controlling the fluxes and speciation of contaminants in both aqueous and solid phases is needed to assess future changes in their distribution and bioavailability. This information will be needed for incorporation into appropriate models that will provide adequate description, and eventually predication, of the biogeochemical behavior of contaminants at appropriate spatial and temporal scales in the Gulf. Accurate measurement of the concentration and speciation of both inorganic and organic contaminants using current methods is tedious and expensive, and thus limits spatial and temporal resolution of their distributions and behavior in the Gulf. Consequently it was agreed that there is a continuing need to develop new precise and rapid sensors, preferably for *in situ* use.

Monitoring needs continue to be identified as important. New technology should be used whenever possible to provide high quality data and achieve adequate temporal and spatial coverage. *In situ* monitoring of variables affecting nutrient dynamics appears to be more plausible at this time while that for contaminants still presents formidable challenges. For this reason monitoring efforts for the latter should be well-focused and carefully coordinate and integrate both management and scientific perspectives. Data management remains an integral need in the effort to provide high-quality data in usable form to the diverse audience encompassing the scientific, management and public domains. Both monitoring and database management activities should be viewed as long-term efforts requiring consistent and adequate support to be successful. Finally there was discussion of the interaction of the scientific community with managers. Management questions often lead to, or are compatible with, interesting scientific questions and can therefore be integrated into meaningful research programs that satisfy both scientific and management needs. The product of such research must, however, be in a form that can be readily assimilated by the management community, and the public that both the management and scientific community serve.

Human Induced Biological Change

Two working sub-groups were formed, one to discuss issues surrounding habitat alteration and a second to address contaminant effects. The first sub-group recommended the identification, mapping, and study of ecologically sensitive habitats, and the determination of the effects of mobile gear on form and function of benthic communities, as high priority research areas. Secondary priorities included the determination of thresholds at which the functioning of these habitats becomes impaired, and a study of sediment transport in the Bay of Fundy, a process thought to have been altered by the influence of man-made structures on physical circulation. An improved understanding of linkages between habitats both within and between nearshore and offshore regions of the Gulf was also identified as an important concern. The contaminant sub-groups identified additional research into effects, transport and loadings, risk/hazard analysis, development of management tools, and the continued search for suitable indicator species, as priorities. Of these, research on biological effects, risk/hazard assessment, and the development of management tools (e.g., establishing impact-based acceptable ranges in the concentrations of human and ecological toxins, scientifically-based sediment-quality criteria and other tools designed to support sound management practices within the region) were considered to be of greatest importance. The working group as a whole noted that while many of their concerns addressed elements affecting the formulation of a comprehensive understanding of the functioning of Gulf of Maine ecosystem dynamics, defining which of these issues deserved highest priority was difficult. Establishment of research priorities could benefit from development of appropriate conceptual Gulf-wide model(s). These models could be of use in defining desired end-points regarding the status of the ecosystem(s), and thus help identify the most critical information needs required to achieve those end-points.

Fisheries Issues

The fisheries working group focused on two topics, improvement of the scientific advice used in support of fisheries management and issues associated with the growing aquaculture industry. The fisheries sub-group recognized that the single species approach to fisheries management in the Gulf was appropriate, but that incorporation of ecosystem dynamic considerations into the advice given to managers was a needed improvement in the implementation of this approach. Implementation of multi-species models as tools continued to be hampered by the lack of data, but some models of this type are being developed. Deficiencies in the current single species management strategy identified were: 1) a failure to consider distribution patterns and behavior in the assessment of stocks, 2) unreliable or nonexistent recruitment estimates, 3) inadequate consideration of environmental factors affecting recruitment, 4) natural mortality rates, and 5) vulnerability of target species to fishing efforts. The group identified the need to incorporate more interdisciplinary decision-making processes in assessment of stocks and a need to improve evaluation of enhancement efforts, the process used in the selection of release sites, and the subsequent protection of these sites after juvenile cod are released.

The aquaculture sub-group noted that, with the exception of Brown's plenary talk, most of the presentations at the meeting were concerned about the potential negative aspects of aquaculture on the ecosystem. However, many of the concerns regarding wild fisheries (water quality and disease issues) were identified to be common to aquaculture fisheries as well. Interdisciplinary efforts to establish appropriate physical and ecological criteria used in site selection was identified as a critical need. Additional research into the effects of nutrient loading, monitoring, and the use of chemotherapeutants was considered to also deserve high priority. The sub-group recommended that a more objective and balanced perspective in the resolution of conflicts between traditional and aquaculture fishery interests be implemented. They felt development of models as tools to assist in aquaculture siting, and in conflict resolution, would be beneficial.

Concluding Remarks

It has been my pleasure to serve as conference chair and I wish to thank the many U.S. and Canadian colleagues who have directly or indirectly contributed to its success. In closing, I offer the following remarks.

Ecosystem modeling was an underlying crosscutting theme for this Symposium and Workshop because of its potential for enhancing both scientific endeavors as well as improving support for technically-based management decisions in the Gulf of Maine. In light of the guidance offered by both Eileen Hofmann and Job Baretta it is clear that one of the most crucial steps in achieving this goal has not yet been taken. There is as yet no "over-arching conceptual model" within which development of the necessary sub-models should take place. Establishing this conceptual model for the Gulf of Maine ecosystem(s) should be the next agenda item if the growth and utility of the potentially powerful tools of ecosystem modeling are to be realized. It is clear that producing a fully comprehensive predictive ecosystem model requires a level of detailed knowledge that will certainly not be forthcoming in the near future and that intermediate steps, such as those described by Baretta for the North Sea, would be a more reasonable and realistic objective. At the very least, agreement on the conceptual framework of the comprehensive ecosystem-wide model might stimulate approaches used in the development of sub-models of physical, biological and biogeochemical processes that could be more easily integrated into the larger modeling framework.

It is clear that substantial progress has been made over the last five years in advancing the state of science in the Gulf of Maine region that either directly or indirectly supports development of such models, particularly in the areas of physical-biological coupling. Beardsley et al. (these proceedings) list no less than 13 different efforts in this regard. Progress in understanding coastal current dynamics, particularly with respect to the transport and distribution of red-tide organisms, has been made. On a more local scale, research has dramatically enhanced our understanding of physical, chemical and biological processes in the western Gulf of Maine and has resulted in the production of a water quality model used in support of the difficult decisions being made by the MWRA. While none of these meet the objective of delivering a fully comprehensive ecosystem model, they do demonstrate the progress made and real benefits of intermediate steps that might lead to the eventual achievement of such a goal.

The proliferation of these models raises important questions regarding the ability to sustain and nurture the continued evolution of modeling in the region that retains the best elements of the existing models, avoids duplication of effort, and promotes integration of other system sub-models. A recommendation made in the November 1993 RARGOM workshop on modeling in the Gulf of Maine called for the establishment of an institutional commitment to long-term model development in the region to achieve these goals. An example of the need for such a commitment is the current inability to maintain and support the water quality model developed for the MWRA, despite widespread recognition of its past and potential future contributions to both scientific and management interests in the Massachusetts and Cape Cod Bay area. Such an institutional commitment is also consistent with the need to link long-term monitoring efforts to modeling activities for the mutual benefit of both as discussed earlier.

Important advances in our knowledge of the introduction and cycling of contaminants (nutrients and chemicals of environmental concern) into the Gulf have provided a better perspective on where management activities might be most productive in contemporary and future planning. However the inability to support meaningful monitoring and database management programs at adequate levels remains a conclusion of this workshop as was that of the 1991 Woods Hole Scientific Workshop. There is no excuse from any rational perspective to further delay meaningful consideration and resolution of this problem.

The presentations and discussions in this workshop, and others convened in the region recently, are consistent in identifying overfishing of commercially important fish and shellfish in the Gulf of Maine as perhaps the single largest region-wide environmental impact of human activity. The impact of these activities on the fisheries is far more evident then any known impacts of contaminant discharges of both nutrients and chemicals of environmental concern in the region. As a corollary it may also be concluded that the demise of top predators may have substantial consequences down the food chain that should be considered in any single-species management scenario. The remarkable magnitude of the physical disturbance of benthic habitats caused by bottom trawling activities in the Gulf represents another fisheries-related area deserving far greater attention than currently afforded.

The above observation does not mean that problems associated with the introduction of chemicals of environmental concern should be relegated to one of lesser priority. As population and development of the coastal watershed regions accelerate, and land-use patterns change, there will be increasing economic and political pressure to make sure that allowable inputs are not unreasonable which will require careful planning and assessment of acceptable loadings. This will require more sophisticated understanding of the biological effects of contaminants and the processes controlling their distributions and bioavailability in both the nearshore and offshore regions of the Gulf. The costs involved in the clean-up of Boston Harbor and difficulties in advancing aquaculture interests in the region are two, albeit very different, but useful examples reflecting this type of concern. The growing recognition of the need to understand the linkages between watershed activities and impacts on adjacent estuarine and coastal marine ecosystems offers exciting possibilities for interdisciplinary research and ecosystem model development that address critical management needs. These issues are transboundary in nature and will require close cooperation between Canadian and U. S. scientists and managers.

Finally, one of the key ingredients in assuring that science keeps abreast and meets the needs of the management community, and vice versa, is to facilitate communication between the scientific and management community. This issue was raised at this symposium, as it has been in numerous others, in the concluding panel discussion between scientists and managers and was further discussed at the follow-up science-management workshop held in June 1997 at Sebago Lake in Maine. The report produced by this second workshop is appended to these proceedings. It offers a blueprint for the nurturing and growth of these lines of communication that should promote and support meaningful exchange of knowledge and ideas between the two communities. Both the scientific and management communities, and perhaps more importantly, the public at large, will benefit by this communication in the increasingly complex and difficult times ahead. The dialogue also must be expanded to ensure a meaningful role for all stakeholders in the region (e.g., non-governmental environmental organizations, fishermen, private sector interests, indigenous native populations and others). One of the ways this goal might be achieved is the process of vision-setting presented by Jerry Schubel of the New England Aquarium at the Sebago workshop. Establishment of such a vision for the Gulf of Maine jointly between the scientific community, the management community, and other stakeholders in the region may well be the next logical step as we enter the next millennium. It is clear that we, as members of the international community of the Gulf of Maine, will need to have a firm grasp on what vision we share, the processes by which we can achieve it, and the resources needed to implement those processes. We have made significant progress in the restoration and maintenance of the quality of environment and life in the Gulf of Maine that should serve generations yet to come, progress that must continue if the legacy is to be a long-lasting one.

Department of Fisheries and Oceans Canada

Peter E. Partington

Fisheries management in Canada focuses primarily on the commercial, recreational, and Aboriginal food, social and ceremonial harvest from the wild state.

Commercial harvest has, by far, the greatest impact on the ecosystem, both in terms of removals and methods of harvest, and thus absorbs the major share of fisheries management resources and energies.

Management of these resources is done almost throughout on a single specie approach. We have likely been herded into this approach by being caught up in a complex web of issues such as control on harvest levels, demands for entry by fishers, sustainability of the resource, economic viability and efficiency. While many fishers have been traditionally (and more are becoming out of necessity) multi-specie dependent, the actual measures in place are still based on a single species basis.

All the issues in the web require both a predictive and monitoring capability. It is through improving these capabilities that we will improve our ability to meet the objectives of the Department, conservation and sustainability.

The interactive elements that occur within an ecosystem do not play a large enough role in how we are managing our fisheries today. Knowing more about them will enhance predictability, make monitoring more meaningful, and will ultimately better result in a sustainable resource base.

Current Problem

What is most catastrophic within the Fisheries itself, is the lack of sustainability due to the constant modification in population abundance within fisheries. This has severe economic and social ramifications to the many harvesters in Atlantic Canada. As you know, there are approximately 60,000 fishers in Atlantic Canada and within the Scotia-Fundy sector, which is where I work, approximately 16,000 fishers make all or most of their living from harvesting commercial species of fish. The recent moratoria in fishing for cod and related species in the Gulf, Newfoundland and Eastern Nova Scotia area have created severe economic and social disruptions. This has spilled over into some of the most prolific areas such as Southwest Nova Scotia where major stock declines in the groundfish fishery have caused similar industry problems.

Direction For Future

As such, we need to take a look at how we do business by moving more towards an ecosystem related approach in managing these commercial species - specifically, how inter-relationships within the ecosystem impact upon the resources upon which we depend.

Questions

Given these comments, you have asked: "What do I see as the issues within an ecosystem, research or science approach which need to be answered?" or, "What uncertainties exist within any ecosystem which require scientific advancement so that decision-making can be made in a more holistic fashion using a more knowledgeable base?"

Responses

1. We need to address obtaining a greater understanding of the impact that climatic and other natural occurring events within the ecosystem have on the sustainability and fluctuations within commercial populations.
2. We need to focus on the inter-relationship of commercially and non-commercially harvested species within the ecosystem, specifically, how the modification of any species impacts on others; and
3. What impact environmental approaches which attempt to maintain a "status quo" have on commercially harvestable species.

Details of Issues Presented

Naturally Occurring Events

The first issue I raise relates to activities that are not man-made but which occur naturally, if I may be so bold as to suggest this, and impact the ecosystem. We have recently heard many theories about why Northern cod and the other cod stocks have declined. These theories have varied greatly in their suggestions and in all probability each and every theory has some relative merit to it. This suggests to me that there are a number of environmental issues within an ecosystem which all impact upon the single species or the various species within the ecosystem that are harvested commercially.

Studies and information respecting impacts of changes in these naturally occurring elements would be of incredible benefit in enhancing predictive capabilities as to population sizes, population growth and migratory habits/patterns. For example, in recent studies of 4VsW cod, we have learned that the temperature and salinity within the 4VsW area have changed significantly over the last number of years. We have also learned that the "weight at age" of cod has declined at a rapid rate. This could suggest an inter-relationship that these various issues have with the expected biomass responses from commercially fished species. It may provide the predictive capability that would allow us to better match harvest levels with the available resource.

As you know, one of our major downfalls in single species approaches and the limitations we place on the number of fishers utilizing the resource is that it is very difficult to match harvesting levels to the available resource. Anything that could enhance our predictive capabilities would allow us to better plan for the future and match resource and fisher in a manner in which social and economic disruptions are known well in advance and adjusted accordingly.

Inter-Relationship of Species Within the Ecosystem

The second issue is the inter-relationship of species within the ecosystem. During the recent declines in groundfish stocks, the ingenuity of fishers within Atlantic Canada has come to the forefront. We now have a process in place where we have developing species advisory boards through which new ideas are put forward by fishers for harvesting essentially new species of animals.

One recent proposal was to harvest krill. Many people suggest that species such as krill, capelin, even herring are integral parts of the food chain and their resultant harvest has lead to declines in many of the groundfish fisheries. My concern is that, in the absence of knowledge of the interdependence of various species within the ecosystem, it is difficult (and perhaps risky) for both the Department of Fisheries and Oceans and industry to make rational decisions on new ventures (or not so new ventures), such as the harvesting of herring in groundfish areas and the harvesting of other commercially viable species that may impact upon still other commercial harvestable species. Therefore, before we wander too far down the road of new developing species, we should understand the interrelationships within the ecosystem.

As well, we should also understand the impacts of our harvesting activities that are now taking place within an ecosystem. If we were to have this capability, we might find out that many of our problems that exist today are due to interrelated impacts based upon our lack of knowledge of ecosystem-related matters, resulting in narrow application of our management practices.

There are indeed other examples which are far less direct than the aforementioned krill scenario. There is a major controversy at the present time with respect to the harvest of marine plants in the mid-tidal waters. Many are suggesting that the harvest of large amounts of marine plants which is currently occurring under license will have a dramatic impact upon the ecosystem. This impact may in fact not directly relate to commercial species but may affect the food chain which ultimately could impact upon some of the species which are harvested in the area. Therefore, we need to be able to be predictive in our approach to these types of issues considering both environmental impacts and impacts on the ecosystem and the commercially important parts of that ecosystem from a fishery management perspective.

Impact of Non-Harvesting Activities

The third issue, which is becoming a major issue, particularly within the various parts of Atlantic Canada, is the impact of non-harvesting activities within the ecosystem on traditional commercial harvests. As you are aware, we have many new growth industries such as environmental tours, marine parks, whale watching, etc. which all seek to profit by promoting intact or surviving ecosystems.

These growth industries require major support from a holistic, environmentally sound ecosystem application. This is distinctly different from our current fisheries management approach for commercial harvest. As a result, there appears to be a collision course emerging between commercial harvests and ecotourism activities.

With focused scientific research to determine interrelationships within the ecosystem and how best to approach these interrelationships on a holistic basis, both commercial fishing and ecotourism can occur and be economically viable. If we do not deal with this issue, it will become a major focus for lobbies and protests, and neither the fishing industry nor the ecotourism industry can weather this without significant casualties.

When we talk of significant casualties, we talk about communities and the people within those communities as being the ultimate victims. Therefore, I think it is necessary that we address the issues of whales, seals, porpoises, protected areas, animal rights groups, etc. in a meaningful, holistic scientific manner. In this way, I believe that both the ecotourism and the commercial fishing sector can exist and prosper.

Summary

I realize I have talked from the point of view of commercial fishing and that we have a relatively simplistic harvesting approach which deals with a single species focus. One should not be content that this is without problems nor that it is relatively easy to deal with. As you know, we are experiencing significant declines in many resources - inshore scallops, groundfish and lobster in some lobster fishing areas to name a few. As well, we are into a situation where downsizing has reduced the Department's effectiveness in certain areas of the fishery, leaving the fishers to take an ever increasing role in the management of the fisheries. This approach often creates a confrontational situation between conflicting interests within communities and within geographic locations.

Lack of understanding of the complexities and the intricate building blocks which make up the commercial fishery that we have today will create a continuing situation of tension and produce "me first" attitudes. If we are to move forward, we need to dispel the myths held by all groups with respect to the ecosystem and the various elements which have contributed to the situations that exist today, and replace them with a sounder understanding of the interrelationships that make up the ecosystem.

Conclusion

Scientific research in these areas is, in my opinion, the best way to deliver this message as we attempt to foster a level of confidence through provision of the much needed answers that all of us require if we are to better address all of the issues coming forth.

Therefore, I encourage you to look at the commercial, recreational, and Native food, social and ceremonial fisheries as being the manifestation of an important aspect of ecosystem management, and one that will need to be fostered, encouraged, nurtured and developed in the future so that sustainability of fishers and their communities can occur as a result of this overall ecosystem approach.

For us to be successful, and for the fishing industry to be successful, we need to know the answers to all of these questions. Your help will be invaluable.

Environment Canada, Atlantic Region

George Finney

In 1994, Environment Canada biologists measured changes in the distribution and characteristics of the sediments in the Bay of Fundy mud flats, and of the invertebrates that live in them. The changes raised concerns over implications for food chains that depend on these animals, and which could affect the numbers and distributions of internationally important bird populations, particularly the huge flocks of sandpipers and phalaropes which refuel in the Bay on their southbound migrations. Discussions with scientists in other agencies indicated that many diverse changes were taking place in the Bay, although the links to each other, to natural cycles or to man-induced causes, such as the damming of river mouths, resource extraction or toxic chemicals, were unknown. These changes range from reductions in salmon numbers and expanded ranges of lobster to increased erosion of some headlands.

Many of these issues of concern to Environment Canada in the Bay of Fundy and Gulf of Maine are discussed and clarified in the draft report entitled *Fundy Issues - Information Up-date and Workshop Synthesis.* This scoping paper was drafted by the Fundy Marine Ecosystem Science Project steering committee, a group of government and university scientists with expertise on the Bay of Fundy. It served as background to a scientific workshop held in Wolfville, Nova Scotia in January 1996, and is being up-dated for publication as an Environment Canada Occasional Paper this fall. Although the following text refers to the Bay of Fundy, the same concerns apply to varying degrees throughout the Bay of Fundy - Gulf of Maine system.

The key issues for Environment Canada that the scoping paper identifies, and which require further research to ensure that managers can make the best decisions respecting the Bay of Fundy, can be summarized as the following:

1. knowledge gaps concerning the ecosystem linkages and trophic structures of the Bay of Fundy,
2. impacts of resource harvesting on key components of the Bay of Fundy Ecosystem, and
3. impacts from land-based activities on key components of the Bay of Fundy Ecosystem.

Knowledge Gaps Concerning Ecosystem Linkages and Trophic Structures

The first issue generally reflects the uneven state of knowledge of natural physical, chemical and biological processes taking place in the Bay of Fundy, most of which stems from studies conducted in the 1970s when tidal power projects were proposed for the Bay. These knowledge gaps make it increasingly difficult to assess the impacts of various human activities taking place in and around the Bay. Many of these aspects require the expertise of scientists in other government agencies, universities or private industry, and must be studied using interdisciplinary cooperative approaches.

Ecosystem linkages start with the physical processes that take place in the Bay, where a clearer understanding of hydrodynamics and sediment dynamics is needed. Refinements of the present hydrodynamics models, such as the FMG model which applies to the whole Fundy-Gulf of Maine system, and more specific models that address limited areas such as the Shepody Bay system, or aspects such as tidal surges, are required. These will enable us to consider hydrodynamic questions such as the influence of the natural 18-year cycle of tidal energy in the Bay, or implications for rising sea level related to climate change. It is then important to consider the erosion, movements and deposition of sediments, as these control the characteristics of subtidal, intertidal and salt marsh substrates which are important for many lower trophic levels in the Fundy ecosystem.

Our knowledge of the biological components of the Fundy ecosystem is greatest for higher trophic levels such as the shorebirds that gather on the mud flats of the upper Bay, the endangered Right Whales of the lower Bay, or harvested species such as finfish or lobsters. However, the primary and secondary producers on which they depend, and the factors that control their productivity are still very poorly understood.

Consider, for example, our scientific knowledge of factors affecting the food chains that support hundreds of thousands of Semipalmated Sandpipers *(Calidris pusilla)* as they feed on the mud flats in August to refuel for their trans-oceanic flight to South America. They feed primarily on the crustacean *Corophium*, a small mud-dwelling amphipod which in turn feeds largely on benthic diatoms which cover the surface of the mud. Although the food chain is short, we are unable to explain recent declines in the numbers of *Corophium*, which may have reduced the ability of sandpipers to feed effectively, forcing them to stopover for longer periods in the Bay. Changes in the size composition of the mud flat sediments and increases in their water content may have reduced the potential of the mudflats to support the invertebrates, or the diatoms on which they feed. Without a better understanding of the ecology of each link in such food chains, it remains very difficult to identify conservation actions that can be taken to resolve such problems.

Impacts of Resource Harvesting

The most obvious immediate threats posed to the Fundy ecosystem are the impacts of resource harvesting. These include traditional activities such as the herring fishery, the lobster fishery and shellfish harvesting. Although these activities have been undertaken over a long period of time, there are recent indications that they may be having serious impacts on other species or on the substrate itself. For example, new underwater scanning technology has shown deep scars on the sea floor which result from dragging for shellfish, and which may have removed the gravel surface layer in some places, exposing the layers of finer sediments below to rapid erosion.

Newer activities may present additional problems. Recent research at Acadia University supported by Environment Canada showed that the "low-tech" digging activity of baitworm harvesters on the Minas Basin mudflats disturbed the invertebrates in the upper layers and reduced the feeding efficiency of shorebirds by up to 50%. Similar concerns for the quality of the rocky intertidal areas that serve as brood-rearing areas for eider ducks and feeding areas for many fish may be adversely affected by increased rockweed harvesting activity. Aquaculture activities along parts of the New Brunswick coast are likely to be affecting the productivity and benthic species composition due to the provision of extra food, and the use of chemicals, on both local or regional scales. The escape of many farmed salmon has already markedly changed the genetic composition of salmon found migrating up the streams that feed the Bay of Fundy.

Resource extraction is not limited to renewable resources. In addition to the traditional removal of sand and gravel from beaches, the construction industry is now assessing the potential for the removal of aggregate for road and building construction from subsurface deposits in the Bay. The potential ecosystem impacts of these activities that could change the sediment dynamics are particularly hard to forecast.

Impacts from Land-based Activities

Many of the stressors that affect the Bay of Fundy actually result from human activities on lands adjacent to the Bay or which are drained by rivers that flow into it. The chemicals that are applied to farmland in the Saint John and Annapolis valleys as pesticides and fertilizers, for example, often end up in Bay of Fundy waters, as do residues of pesticides applied to our forests. Soil eroding from farmland, forestry operations, road and other construction activities often reaches the Bay through streams and rivers, as does a range of untreated and incompletely treated waste from municipal and industrial sources. The amount and timing of the arrival of these sediments and compounds in the Bay is affected by the dams and barrages that now cross most of the rivers and streams that formerly flowed unimpeded into the Bay of Fundy. Airborne pollution from Maritime sources and those farther up-wind add to the chemicals circulating in Fundy waters.

A few of these pollutants, such as mercury or PCBs, have been measured in high enough concentrations by themselves to affect the health of top predators in the food chains under normal circumstances. However, when stressed by other factors, or in combination with the effects of other chemicals, it is likely that many of these compounds are having important sub-lethal impacts on the health of many species. Research on the impacts of these chemicals must take place in the Bay, while studies to identify sources and pathways, and to find ways to reduce the incidence of harmful chemicals, must take place where the products are released.

Summary

It is apparent that many of the concerns identified by the Fundy Marine Ecosystem Science Project and Environment Canada can not be addressed using the limited resources of one department alone. The most important priorities must be agreed on by all agencies with an interest or expertise in the Bay of Fundy ecosystem. These must then be addressed through the use of interdisciplinary teams of scientists using an ecosystem approach, whose long-term goal is to provide the information needed by conservationists and managers to improve the environmental quality of the Bay of Fundy. The Fundy Marine Ecosystem Science Project team has already developed a research action plan that identifies areas of priority research and the agencies who could contribute. It is important that these studies be undertaken together with other partners in RARGOM who are addressing similar issues in the Gulf of Maine, and this meeting may provide an important opportunity to link such initiatives.

Maine Department of Marine Resources

Robin Alden

Introduction

The question posed is an excellent one: "What are the top three issues that will require scientific research to reduce uncertainties in my decision-making process". When one is, as I am, in a position of responsibility for an area's fisheries resources, what overwhelms one is the degree of uncertainty in every single fisheries decision. Our ignorance is so profound that even common sense may not be a good guide, because common sense requires an understanding of the basic frame of reference.

There is much we do know about fish and fisheries. Assessment and population dynamics give us a basic framework in which to operate. But it is terrifyingly clear to me that this type of information is not enough. Given the human distaste for difficult decision-making, especially in the face of uncertainty, it is all too seductive to oversimplify our model of the world and assert that those disciplines do provide adequate basis for our decisions. That makes it easier for both the decision makers and those interest groups who bear the immediate consequences of those decisions. The fishery management community's highly simplified model of the fisheries ecosystem, enables there to be certainty, within that model, about the "right path". But it is essential that fisheries managers not be deluded by that false certainty. The resource and the industries which use the resources, will be much better served by a more humble, more scientifically curious approach.

There are numerous political and legal obstacles to such a position. In the last year and one half, I have certainly found that being frank about the fact that we do not have the science to say that a given decision is based in definitive knowledge greatly agitates the regulated community and their attorneys. The alternative — taking stands based on an assertion of confidence — is antithetical to scientific discovery. It polarizes and entrenches, and decreases the possibility that the right questions will be asked or that new answers will be found. In short, it decreases the possibility of adaptation to new knowledge or to real change in the ecosystem within which we manage.

For this reason, the Maine Department of Marine Resources will, from now on, publish a research agenda regularly in which we state, as managers, the types of research we most need to have done. Until we state clearly what we don't know, we can never generate the scientific work that can get us that knowledge.

All of my comments below are based on the following assumptions. It is important to know the population levels of the fish we are trying to manage. However, this by itself is not enough. In the same way, fishing mortality controls, though important in many — perhaps most - cases, are not enough for successful fishery management.

Life history and behavioral information

We need to have complete life history and behavioral information, with an ecological orientation about each species managed. The life history and behavior information is particularly important for the age zero to recruitment period and for the significant breeding population.

It is this information that will give us the tools to go beyond simply controlling fishing mortality and lead us to understanding the "critical control points" for species we manage. To be sure, within the current assessment models, this information needs to be incorporated into the terms of reference, and indeed into the structure of the models we use for assessment. But we must go further in using this information. It can tell us what are the controlling factors for those species' life cycles. Once we start looking and seeing at this basic level, we will be looking at information that is far more stable than the highly variable annual recruitment and should lead us to much more significant management actions.

We are all groping toward ecosystem management, a mission we must achieve. This is one route toward that. We do not need to know everything about the basic biology, physiology, and behavior of every life stage of every species in order to achieve ecosystem management. But each piece of local, specific information is another layer that will inform us about the significance of habitats and fish behaviors. As we learn these things: what is significant for successful lobster settlement, or the distribution of plankton across a groundfish juvenile bottom with resultant separation of flounder and groundfish juveniles, we will start to build new models about what is important. This information is enduring, and I suspect it will lead managers to give far more weight to decisions about how, when, and where fishing is carried out.

We lack such basic life history information and even age and growth information for many commercially important species. The list includes "new" commercial species such as whelks, sea urchins, sea cucumbers, seaweeds, periwinkles, eels. And we need far more detail for old standbys: cod, lobsters, herring, and soft-shelled clams.

Questions such as whether cod home to natal spawning areas must be resolved if we are to manage them effectively. Is such behavior genetically determined, or it is learned behavior? We know that herring do home to natal spawning areas, but do they travel in schools from their spawning area? Do, in fact, large populations of breeder lobsters gather in the deep water off our coast?

I often compare my position as a fishery manager with those of my fellow cabinet members responsible for management of forestry of inland fish and wildlife. Managing mammals is quite simple when you compare understanding juvenile nutritional needs for a mammal to those of a cod or herring larvae. My land-based colleagues have the luxury of resource mapping of a quality, however imperfect, that would make a marine fishery manger green with envy.

So, if we piece together the information, species by species, locale by locale, — that the red hake need shelter in the scallop shell, why and how lobsters move and sort themselves by sex, and so forth — we will start to develop an understanding of the Gulf of Maine that will change our mental model of the system.

Appropriate Management Unit

We need to identify the appropriate size of management unit. Current United States management strategies are based on such principles as "throughout its range" and the constitutional rights of access of state fishermen to all state waters and all federal waters. While this may be appropriate for some highly migratory species, it is completely inappropriate for pandemic stocks which maintain numerous self-sustaining populations. We are increasingly aware that this approach may expose species that have local populations that are sedentary or make limited migrations to excessive fishing power. This is particularly true for fisheries managed by quota, as opposed to by input controls, which are operable on the local level.

While we have learned that herring actually is made up of local stocks which migrate and mix, we in the United States are still assessing that stock on a coastwide basis. For a manager, that provides not just useless advice — it provides dangerous advice because it implies to the business community that a removal in one time and place is identical in value to herring sustainability of that of a removal in another time a place.

We currently manage ocean quahogs uniformly throughout the East Coast, with one minor exception for the eastern Maine fishery. This is managed differently only because the fishery is socio-economically so different from that of the Mid-Atlantic and was forgotten in the initial design of the management system. In fact, it is likely that there is good biological reason to manage that stock separately. Recruitment to that population may come from that stock itself or from Canada — we currently do not know. If the Mid-Atlantic boats came to Maine to harvest within an overall East Coast quota, that local stock could be severely over fished.

We are currently managing illex squid on an United States East Coast basis. Once again, an aggregate quota could lead to terrible consequences depending on the true interaction of Gulf of Maine and Canadian illex populations. We need to know far more about the interaction, migration, and reproductive strategies of illex to make sensible and prudent decisions.

We should be seeking stock information that allows the management area for local stocks to be limited to the geographical boundaries needed for that stock segment to be self-sustaining. Habitat and biological communities critical to each life stage of the species within this area should become part of management's portfolio as should an understanding of larval subsidy and/or transport. This can provide the manger with the information to design restrictions that actually protect that stock segment.

Institutional Structures that Foster Stewardship

We need to research other management and governance models that can support and nurture not only stewardship but also enable both enhancement and aquaculture.

Fishery management takes place in a dynamic environment ecologically and economically. It also takes place in an environment characterized by uncertainty. That uncertainty is so profound that even cause and effect are not always clear.

In this environment the command and control model — which we all default to when stressed — is not the answer. If local phenomena are the controlling factors ecologically, then institutions should foster the development and use of local knowledge. If the system is difficult to control, then institutions should foster those controls we can assert. And if measurement and evaluation is fundamentally divisive because of a lack of common perceptions, then the institutions should foster joint learning.

We should not have to argue that the current institutional structures in New England do not work. The local management embodied in the regional fishery management council is not local enough to make a substantive step away from top down management.

From the State of Maine's perspective, the results have been disastrous. Limitations on the fleet are in the process of destroying the community-based, small scale fisheries and are now making the remaining offshore fleet less than secure.

Lobster is now managed by states in state waters and by a federal limited entry program outside three miles. Previously, lobster was managed by size limits and gear limitations and entry and local practices such as numbers of traps and v-notching, were regulated by the industry itself through territories. Although this was "outside the law", in fact this worked better than the current practice. Everyone is aware that lobsters move inshore and offshore seasonally. We now have a situation where local lobstering communities have no control over who fishes the nearshore and offshore segment of their lobster population or how they are fished. The result is a lowest common denominator behavior. Clearly this is an institution that does not work.

With the initiation of seven lobster zone management councils in Maine, we are starting to search for — in practice — a better institution for lobster management decisions than the state legislature and regulatory procedures. We are also exploring qualification-based entry criteria with a lobster apprenticeship program. We would be far better off if more research — into models such as the Japanese co-ops, and many others, had been done before law-making.

Stewardship, enhancement, and aquaculture are all included in the requirements for a successful institutional structure. It is probably far easier to design a structure that serves either wild fishery conservation and management or aquaculture singly. However, it is clear to me that the long term, best use of the Gulf of Maine is one of diversified uses that include a blurring of the lines between aquaculture and fishing. Certainly habitat issues will require that decision-making about aquaculture and fishing overlap.

Our institutions need to develop and use the local ecological information available from both the scientific community and the industries which use the resources. They need to develop an ongoing process for exchange of information and learning from that information. They need to provide a mechanism for articulating common goals and provide reward for responsible behavior. And our institutions need to develop evaluation criteria that are respected by all those involved. It is worth putting the research into making this possible. There is so much at stake.

Massachusetts Office of Coastal Zone Management

Peg Brady

In reviewing the Massachusetts coastal program and evaluating three program areas that will receive a significant amount of time and financial investment over the next five years, the following three major scientific needs emerge for Massachusetts coastal waters and habitat:

1. An assessment and quantification of the relative impact of cumulative stressors on coastal watersheds with a particular emphasis on point source and non-point source contaminants. In addition an evaluation of mitigation measures (e.g., storm water best management techniques) currently being promoted is crucial.
2. An assessment of methodology proposed for restoring injured marine resources with a particular emphasis on salt marsh systems, fish spawning areas and shellfish habitats. An evaluation of restoration monitoring strategies will be needed.
3. An evaluation of dredge disposal techniques including upland, nearshore and subtidal disposal alternatives.

Cumulative Impacts On Coastal Watersheds

Massachusetts environmental agencies have undergone a reorganization in their approach towards water resource decisions. Prior to the reorganization, water resource decision-making (i.e., NPDES renewals) was solely based on a chronological schedule. Permits to discharge effluent and withdraw water were never considered on a watershed context. Currently, greater emphasis is placed on assessing the relative contribution and impact of point and nonpoint source contaminants within a watershed and identifying key targets for cost-effective remediation.

Even though the decision-making process has been modified appropriately, assessing and quantifying the relative impact of point versus nonpoint loadings continues to be more of an art rather than a science. Watershed planning and management within complex urbanized watersheds continues to be an extraordinary challenge.

Scientific research is needed to focus on identifying cost effective monitoring and assessment techniques on the watershed level. A particular emphasis must be made on the relationship of the coastal watersheds and nearshore coastal waters. In addition, solutions to reduce contaminants must be carefully evaluated, especially in the context of environmental gains and their relative cost.

Restoring Injured Marine Resources

Large sums of funds are being expended to restore injured natural resources throughout the United States. In Massachusetts alone, millions of dollars have been acquired through litigation and settlements brought against parties responsible for the release of hazardous substances to the environment. By law the funds may only be used to restore, replace and acquire the equivalent of the injured resource. In the case of New Bedford, federal and state agencies documented injuries to marine sediments, fish, shellfish, as well as the water column caused by parties releasing PCBs into the harbor. As a result, over $20 million is available to restore areas such as salt marshes, water column, habitats, living resources as well as endangered species.

Techniques to restore injured resources are not readily available to resource managers nor is there a body of information available documenting the success of techniques currently being utilized. With greater emphasis placed on restoration of marine waters and habitats resource managers will need strategies to address resources targeted for restoration. A restoration strategy developed in the context of coastal watersheds is an ideal approach.

Disposal of Dredge Material

Massachusetts is developing a statewide dredging and dredge disposal plan for the state's most active commercial ports. Urban ports in need of dredging currently face a difficult and expensive process of finding safe disposal alternatives.

To address the problem and expense required to dispose of contaminated harbor sediments, Massachusetts passed the 1996 Seaport Revitalization Bond which provides funds to develop plans that will identify disposal remedies and sites for these materials. Importantly, the planning process will address long-term capacity issues, and will also address dredged material from both public and private areas.

Massachusetts ports typically contain contaminated sediments. The cost of the environmentally-safe disposal of contaminated dredged materials is exorbitant, dwarfing all other costs of the dredging process. The disposal of contaminated materials is the primary cause for the long and expensive permitting process required for dredging in urban harbors.

To assist the promotion of the maritime industry, state agencies are re-evaluating the environmental review process to accommodate a timely and regular dredging schedule; and, secondly, increasing the state's funding commitment for dredging and the disposal of dredge material.

The safe disposal of dredge materials is an extraordinary challenge for coastal communities. Identifying alternatives for dredge material disposal not only for the short term but also for the long term needs will require a regional approach. Currently, Massachusetts is exploring a regional approach for beneficial uses of uncontaminated dredge material, but few publicly accepted alternatives (i.e., incineration, confined disposal, borrow pits, etc.) exist for the disposal of contaminated material.

New Brunswick Department of Environment

William C. Ayer

Today, the Gulf of Maine is confronted with an ever increasing number of local and regional environmental stresses. Appropriate responses to the various pressures on the systems in the Gulf will require a science based approach to deal effectively with the many uncertainties. Clearly, for those making decisions requiring sacrifice or change in society, management of the uncertainties will be of vital importance.

As a point of embarkation, a review of the issues as seen by scientists working in the Gulf is useful. The Proceedings of the Workshop convened by the Regional Association for Research on the Gulf of Maine on the Cumulative Impacts of Multiple Stressors has been extremely helpful in this regard (RARGOM 1996). Additionally, a similar review and analysis of the key issues has been produced in a recent National Research Council report on coastal ecosystem science (NRC 1994). These two documents, plus my own experience in working with coastal zone issues from a manager's viewpoint have lead me to chose the three issues that I feel will need further scientific study in the near future.

Climate Change

The first of the three is climate change. Whilst the experiment in contamination of the atmosphere continues, there remains a great deal of uncertainty with regard to whether climate change is actually occurring. Greenhouse gases are increasing in the atmosphere, primarily carbon dioxide, nitrous oxide and methane, and these in turn can have a warming effect. The causes of the increase are associated in the main with a rise in the consumption of fossil fuels for energy, land use changes and agriculture. The changes in the atmosphere are projected to result in changes in climate and parameters related to climate including temperature, precipitation, soil moisture and sea level (IPCC 1995). The International Panel on Climate Change report also projects an increase in global mean surface temperature of 1-3.5°C by 2100 , and an associated sea level change of about 15-95cm. As well, simulations show a reduction in the strength of the north Atlantic thermohaline circulation (IPCC 1995).

In the Gulf of Maine, changes in climate with related sea level effects could possibly affect some key physical characteristics of the Gulf such as water temperatures, insolation, wind speed and circulation patterns with impacts on virtually all aspects of the ecosystem (RARGOM 1996). Sea level rise in Atlantic Canada would affect some low-lying areas resulting in flooding, erosion, salt water intrusion and water table rise (Environment Canada 1994). It should also be kept in mind that the predicted impacts would be imbricated onto changes to coastal ecosystems already impacted or stressed by pollution and physical modifications.

There are many uncertainties associated with the climate change issue confronting society, especially the ability to predict and detect future climate change with related impacts. This is particularly so on a regional scale as in the Gulf of Maine. Additionally, our understanding of many critical processes is limited and systems are subject to climatic and non-climatic events with frequent non-additive responses (IPCC 1995). In the face of all of this, decision makers must now deal with issues like climate change that are extremely complex, frequently uncertain, spanning longer time periods and worst of all, possibly irreversible in nature. How should we deal with the issue? Should we take the ostrich approach and assume that our present information is insufficient and that the whole matter is an overblown non problem that if ignored will eventually go away? Or should we hedge our bets and take a precautionary approach to the issue? In addition to cutting greenhouse gas emissions, and adopting adaptive technologies and approaches, much science can be done in the face of uncertainty. The most immediate need that seems apparent is to produce indices of ecosystem health in the Gulf's systems that will allow monitoring to record whether change is occurring and if so, at what rate.

If we take a precautionary approach, it behooves us to begin at once to conduct a comprehensive Gulfwide assessment of the necessary science and decision making networks to accelerate and coordinate our efforts regarding emissions, research and adaptive strategies. The costs of not moving ahead may simply not be acceptable on either environmental or economic grounds.

Nutrient Enrichment

Many estuaries and coastal marine systems receive increased nutrients from numerous sources. These include point sources from domestic and industrial wastes, non-point sources such as storm water and agricultural runoff and atmospheric deposition. Some of the excess nutrients make their way into coastal systems via rivers, or directly to estuaries and bays. The increase in the rate of production of carbon in a system caused by the addition of nutrients may result in significant changes in ecosystems. The excess nutrients can produce shifts in species composition and the depletion of dissolved oxygen (RARGOM 1996).

In most estuaries and coastal systems, nitrogen is the limiting nutrient although other elements can in certain circumstances be limiting (NRC 1993). Nitrogen loading is directly related to population density with the greatest loadings occurring near large population centers (Pederson 1994). In New Brunswick, the Saint John River contains the largest portion of province's population and is a major source of nutrients to the Bay of Fundy (NOAA 1994).

Although poorly understood in the Gulf of Maine, toxic algal blooms may be linked to the addition of excess nutrients and/or metals (RARGOM 1996). In the Bay of Fundy, toxic algae blooms have resulted in paralytic shellfish poisoning (PSP) and amnesic shellfish poisoning (ASP) (Environment Canada 1994). Closures of shellfish areas as a result of shellfish poisoning has caused a significant loss of revenue to the shellfish industry. Careful review of data in Atlantic Canada strongly suggests an increase in the intensity and duration of blooms (Environment Canada, 1994).

In New Brunswick, nutrient levels in the Saint John system are high enough to cause algal blooms in headponds and the upper Saint John Estuary. It is not certain, although it has been suspected, that the nutrient levels in the system may cause enrichment or eutrophication of the lower estuary. Gillis (1974) recorded high levels of nutrients in the estuary but could not completely explain the reasons for the lack of plankton blooms. He suggested high water color as a possible explanation. Steeves (1979) reported that the central Saint John River appeared to be heavily polluted with nitrogen and phosphorus. Unfortunately, no definitive recent work has indicated that eutrophication of the estuary has or has not taken place, and it is highly probable that the river remains a major source of loading to the Saint John Estuary and the Bay of Fundy.

In New Brunswick's estuaries and bays, and I suspect in many other major estuaries and bays in the Gulf, there is a strong requirement to establish thorough monitoring and studies on the impacts of excessive nutrients on ecosystems. As well, a careful assessment of the levels and role of atmospheric inputs of nitrogen should also be determined. Without cause and effect information, the very real possibility of enrichment of systems in the Gulf will not be sufficiently understood. On a related note, more work should be directed at toxic algae blooms to determine the relationship, if any, with nutrients and/or other environmental factors.

Every effort should be made to improve on and trial the use of appropriate non-point runoff models for the Gulf researchers to make more accurate predictions of nutrient loadings to coastal systems. Today's models, which are based on the Universal Soils Loss Equation, do not seem effective in northern regions of the Gulf of Maine Watershed. We must also develop environmental indicators that are condensed and transparent enough to sense the health of the Gulf's ecosystems at a glance. This may seem like a tall order; however, with the recent advances in computer and space technology, it should be possible. We have been able to place astronauts on the moon, we should be able to apply similar advances to some pressing issues right here in the Gulf of Maine.

Habitat Change

Physical alteration and habitat loss may not seem significant if the changes are considered on a case by case basis. However, when the modifications are viewed in a cumulative manner, an entire population can be placed at risk. Examples would include the possible negative impact on an intertidal soft-shelled clam resource in a harbor, or the loss of a specific type of benthic habitat. As well, natural changes may be complicated by the effects of various projects or developments in coastal areas.

An example of a particularly destructive type of coastal alteration is the construction of causeways in estuarine situations. In some cases, causeways constructed for transportation purposes have resulted in significant change and damage to natural systems in Atlantic Canada (Environment Canada 1994). In the Petitcodiac River near Moncton, New Brunswick, the causeway constructed in 1967 has led to significant declines of runs of anadromous fish including Atlantic Salmon, American Shad, Alewife and Smelt. It is disturbing to consider the possibility that the once populous runs of Atlantic Salmon in the river have been extinguished. The causeway has also created a damming of the upper end of the estuary and complicated significantly, pollution control options. By slowing circulation, the causeway has resulted in excess siltation of all of the lower estuary. Similar effects have been recorded below a causeway at Windsor, Nova Scotia. Siltation at this site has deposited a layer of silt 2m thick for 2km down the Avon River (Environment Canada 1994).

Other significant changes in the Bay of Fundy have resulted from the dyking and filling of salt marshes. Since the beginning of European development, over 85% of the original salt marshes in the Bay have been altered (Harvey 1994). It is doubtful that such profound alteration of salt marshes has occurred anywhere else in the Gulf of Maine.

One also has to wonder about the potential impact on the Bay of Fundy and the Gulf from the significant tonnages of sediment which come down the Saint John River as a result of soil loss from the extensive potato fields in the upper part of the watershed. Soil loss from fields in the system has been measured at 38tonnes/hectare/year (Chow et al. 1990). The annual on-farm cost of erosion in the potato belt in New Brunswick has been estimated at $10-12 million (Fox and Coote 1986).

Tidal power facilities can render significant changes to coastal systems. From 1980-84, a tidal power facility was constructed at Annapolis River, Nova Scotia. The environmental consequences of this facility have been more extensive than originally predicted (Environment Canada 1995).

There are some steps that can be taken to deal effectively with physical alterations and habitat losses in the Gulf. Perhaps the most important is to establish some form of an integrated process to review and place in context the predicted impacts from all proposed developments in the Gulf which have the potential to damage or destroy habitat. Presently, there are environmental assessment procedures in both Nova Scotia and New Brunswick which deal with projects of certain types and sizes. In New Brunswick, many of the smaller projects of an incremental nature are not caught in the screening net and therefore are frequently not reviewed. Some of these may get picked up in a permit to meet a specific department's mandate but there are no linkages to a cumulative impact assessment process.

A thorough review of the possible impacts of transported sediments from land to coastal systems should be initiated at once. Gulfwide water quality monitoring networks should be established into which a sediment sampling plan could be integrated. A strategy for sediment transport will also be useful as other contaminants such as phosphorus, metals and organics are often attached to sediment particles.

Although recent alterations in salt marshes have slowed compared with the past, the existing losses at various places in the Gulf, particularly in the Bay of Fundy, have been extensive. It is not known what impact marsh reductions have had on the Bay, and if rehabilitation of the marshes should be considered.

Presently, there are two priority habitat exercises underway in the Gulf which are funded through the U.S. Environmental Protection Agency and conducted by the Gulf of Maine Council. The two projects are twinned efforts, one in Great Bay, New Hampshire and the other in Passamaquoddy Bay, New Brunswick/Cobscook Bay, Maine. Both of these projects are patterned after another very similar effort in Casco Bay, Maine. Serious consideration should be directed at expanding these or similar studies Gulfwide as they can provide a great backdrop for decision-making.

Finally, work is required to review the opportunities in each jurisdiction for a Gulfwide riparian zone strategy. Again, this would put into context where these zones should be utilized, and what effect they might have in contaminant control and protection of sensitive or critical habitats.

This paper has reviewed briefly three key issue areas in the coastal zone and has suggested some possible directions to strengthen future management opportunities in the Gulf. As scientists and managers, we will probably not have the luxury of being able to gather more data and conduct more research in the future that is neither practical in terms of funding, nor contemporary considering the magnitude of the issues facing the Gulf of Maine. There is a compelling need to review the scientific/management interface and to link science to the decision-making process.

Scientific information should be available in a form that will influence the critical decisions in the Gulf. A case in point would be the proceedings of the recent workshop on cumulative impacts published by RARGOM. Are the findings in this excellent document read and integrated into governmental decisions on, for example, budgets, legislation, projects, etc.? In New Brunswick there is no arrangement to insure that science underpins key decisions which could impact on the ecosystems in the Bay of Fundy and the Gulf of Maine. An environmental assessment procedure exists, but it responds to a fairly narrow range of project driven triggers. There should be a framework or advisory process into which decisions on incremental and cumulative impacts in the Bay can be reviewed and the best advice forwarded to government. In fact, a science advisory structure could advocate prioritizing existing use of scarce resources as well as reallocation of the same resources to new directions.

Scientists should be represented through some form of standing advisory structures as valued players in an integrated coastal zone management process. Only in this way, can we hope to sustain the Gulf's Ecosystems and to optimize and manage the uncertainty aspects of all the critical decisions ahead. To do less could result in the loss of habitats and species one after the other, or to possibly face the collapse of additional stocks of commercial species. Even if we are unable to prevent problems in all cases, we can still adapt strategies which will pay dividends environmentally and economically as we move ahead.

References

Chow, T.L., J.L. Daigle, I. Ghanem, H. Cormier. 1990. Effects of potato cropping practices on water runoff and soil erosion. *Can. J. of Soil Sci.* 70:137-148.

Environment Canada. 1994. *State of the Environment in the Atlantic Region.* Minister of Supply and Services. Ottawa, 457p.

Fox, M.G. and D.R. Coote. 1986. *Preliminary Economic Assessments of Agricultural Land Degradation in Atlantic and Central Canada and Southern British Columbia.* Regional Development Branch, Agriculture Canada, Ottawa.

Gillis, G. 1974. An Ecological Survey in the Saint John Estuary. The Saint John River Basin Board. *Report No.15h.* New Brunswick Dept. of the Environment. Fredericton, N.B. 64p.

Harvey, J. 1994. *Turning the Tide.* Conservation Council of New Brunswick Inc. Fredericton, N.B. 88p.

IPCC. 1995. *Climate Change 1995: The IPCC Second Report.* The International Panel on Climate Change. Cambridge University Press.

NRC. 1994. *Priorities for Coastal Ecosystem Science.* National Academy Press. Washington, D.C. 106p.

NRC. 1993. *Managing Wastewater in Coastal Urban Areas.* National Academy Press. Washington, D.C. 477p.

NOAA. 1994. *Gulf of Maine Point Source Inventory.* Strategic Environmental Assessments Division. Silver Spring, MD. 11p.

Pederson, Judith. 1994. Impacts of contaminants and nearshore pollutants on habitats in the Gulf of Maine. In *Gulf of Maine Habitat: Workshop Proceedings*, eds. Stevenson, D., and E. Braasch, RARGOM Report 94-2. Dartmouth College, N.H. 180p.

RARGOM. 1996. *The Health of the Gulf of Maine Ecosystem: Cumulative Impacts of Multiple Stressors.* RARGOM Report 96-1. Dartmouth College, N.H. 180p.

Steeves, A.L. 1979. *Nutrient studies of the Saint John River.* MScE Thesis. University of New Brunswick, Department of Civil Engineering, Fredericton, N.B. 335p.

New Hampshire Department of Environmental Services

Chris Simmers

Shellfish Bed Closures

Among the following topics, I rank shellfish bed closure as most important. There are gaps in our scientific knowledge about the health effects of exceeding the current standard and the criteria for closing beds because of proximity to POTW's. In effect, the National Shellfish Program has established extremely conservative criteria which may never be met. A new look should be taken at these criterion.

Atmospheric Deposition: Relative Contribution to Water Quality Impacts

Nitrogen loadings

Nitrogen is considered to be the limiting nutrient in most coastal waters. Is nitrogen limiting in New Hampshire coastal or estuarine waters? Do hypoxia or other nutrient enrichment problems exist in New Hampshire coastal waters? In other words, do we need to be concerned about nitrogen loading into our coastal areas, and if so, what are the relative contributions of atmospheric deposition, point discharges and nonpoint runoff. (My belief is that nutrient enrichment is not a problem in our coastal waters, but I have no data to back up that belief).

Metals deposition

Metals can be toxic, both to aquatic organisms and those that feed on aquatic organisms (such as man). Mercury in particular tends to biomagnify throughout the food chain. What are the mercury levels in shellfish and finfish in New Hampshire coastal and estuarine waters? If mercury concentrations are high, what are the relative contributions of atmospheric deposition, nonpoint runoff and point discharges?

Atmospheric deposition of mercury has other research needs not specifically limited to coastal waters. What is the magnitude or present mercury deposition in the state? What are the regional sources and relative contribution of this mercury? How do contemporary inputs compare to historical levels? What is the persistence of mercury in the environment (i.e., if all sources of mercury were stopped, how long would it take to see reduced levels in fish and other top-of-the-food chain organisms)?

NOAA National Marine Fisheries Service

John Rittgers

I am pleased to have the opportunity to participate in this Symposium and Workshop and to share with you some of the thoughts and concerns that my Agency has for the resources of the Gulf of Maine Ecosystem and issues which we feel are most important to us as we look down the road into the next century.

NOAA Fisheries has a broad range of management and research responsibilities in the Gulf of Maine and its watershed that transcend the four principal themes for the workshop sessions. These are reflected in what we believe to be our Mission, "Stewardship of living marine resources for the benefit of the nation through their science-based conservation and management and promotion of the health of their environment". As stewards, we advocate and practice the sustainable use of living marine resources, both consumptive uses such as commercial, subsistence and recreational fishing, and nonconsumptive uses such as photography, observation, and whale-watching. Our goal is to maximize the benefits to the Nation without compromising the long-term health and biodiversity of coastal and marine ecosystems. We are striving to balance competing public needs and interests in the use and enjoyment of our living marine resources, while preserving their biological integrity.

Many marine species are under stress from over exploitation or habitat degradation or both. Of the United States fishery resources for which we know the population status, 43% are over utilized and 39% are fully utilized. Some populations of marine mammals, turtles and fish are severely depleted or in danger of extinction. These threatened and endangered species are critical to the maintenance of biodiversity, productivity, and the stability of natural ecosystems. Our challenge is to restore these populations of living marine resources to healthy levels living in healthy ecosystems. This will enhance and maintain opportunities for the sustainable use of these resources for present and future generations.

Within the Gulf of Maine ecosystem we are concerned for the long term sustainability of a biologically diverse ecosystem that will support viable commercial and recreational fisheries. These resources are under severe pressure due primarily to the activities of man which compete both directly and indirectly for the critical habitats, and affect water quality and food sources essential to their survival. Often the competitive activities and impacts are obscure at best, poorly documented and generally poorly understood. In other cases, such as commercial and recreational harvest, coastal development, harbor maintenance dredging, and poor agriculture, silvaculture and aquaculture practices, the effects are obvious, quantifiable, and understandable. Fundamental to this concern, and our ability to facilitate management of the living marine resources for this purpose, is a sound understanding of the elements of the ecosystem which are critical to spawning success and recruitment of the various species. To fulfill the vision of sustaining healthy coastal ecosystems, we need increased scientific understanding of the importance of natural ecosystem functions and the adverse effects of habitat degradation and loss, followed by the transfer of this knowledge to those who can apply it to specific resource management issues.

NOAA Fisheries will likely, as a result of amendments to the Magnusson Act, be required to identify the critical habitats for fisheries under federal management. Habitat mapping initiatives will have to be undertaken to meet this short term requirement. It will also be important to undertake the longer term research activity needed to improve our understanding of the basic ecological/ habitat needs of these resources. Such efforts will contribute to a basic understanding of the interdependencies within the ecosystem and thereby enhance our ability to improve upon our collective management and development decisions. To that end, NOAA Fisheries will encourage predictive modeling work that will increase our understanding of coastal ecosystem functions and test their predictions against reality.

The Agency also has major responsibilities, under the Marine Mammal Protection Act and the Endangered Species Act, to recover and sustain populations of species protected under these Acts. Gulf of Maine species of major concern to us in this regard are the Shortnosed Sturgeon, harbor porpoise, seals, and the large cetaceans. Atlantic salmon, not currently listed under the Endangered Species Act, is also of concern to us. Often these responsibilities conflict with our efforts to manage and conserve fishery resources for commercial and recreational benefits. The first step to recovery of an endangered species is usually protection. And with protection comes prohibitions of one form or another. The less we know about the biology and abundance of these species the greater must be our protective measures to comply with the law. This always translates into constraints being imposed on the activities of man which we believe have the potential to "threaten the continued existence" of the species of concern. We continue to seek and evaluate alternative technologies and methodologies for the harvest of other fishery resources that will minimize, hopefully eliminate, the adverse interactions with the protected fish and mammals. Notable in this arena are the ongoing efforts to develop acoustical deterrent devices, gear modification to eliminate entanglements, methods to keep seals out of salmon pens, methods to provide upstream and downstream passage of anadramous fish, gear modifications to reduce the incidental take of regulated species in the northern shrimp fishery. Fundamental to the success of such efforts is an understanding of behavior and the application of that knowledge in the development of new technology.

In our stewardship role we are often confronted by the political realities associated with husbanding a common property resource for the benefit of the nation. Basic science supports the answers given to managers by scientists in response to the age old questions of: "how much can be removed; where and when can we allow fishing to occur; how long before the stock will recover; what will be the impact on prices to the consumer; how can we minimize marine mammal/fishery interaction; where are all the turtles; what are the stock relationships; why can't I have my pier/marina/dock/bulkhead; when is seafood safe to eat/not safe to eat; where can I locate my aquaculture project; what are the conservation consequences of alternative A, B,.....n; etc." The need for improvement in our basic understanding of the biology of these animals and of the ecological dependencies and priorities for survival is self evident.

Socio/Economic data and analysis are typically insufficient or out of date to allow managers to adequately consider the impacts on the industries and communities resulting from their conservation, management and allocation decisions, or to be able to effectively argue the long-term economic consequences of certain actions or inaction. Exploitation of a common property resource has historically focused on maximization of short term benefits with little consideration of the long term consequences of such optimization behavior. We must be able to accurately assess and describe the long term economic and community benefits to an unpopular management action/strategy before we can judge the overall benefit to the nation that may result if enacted. Such assessments require on-going multidisciplinary interactions and collaboration in modeling and reporting to managers. Where traditional market-based valuation methods are not appropriate due to inadequate information or because they undervalue the important components of coastal ecosystems, we will have to develop new methods to value specific habitats and the important functional characteristics of the ecosystems.

Future assessment activities should build on existing information at Federal and state levels to produce innovative, useful, and long-term assessments of the status of the Nation's coastal resources. These assessments will be most useful to managers and policy makers if they provide novel synthesis and prediction of the effects of various anthropogenic perturbations on coastal ecosystems, including:

The significance of watershed or basin-wide diversions of freshwater flows,

The cumulative effects of habitat losses and pollutant loading on living marine resources,

The effects of existing and projected economic conditions and land-use patterns on sources of pollution, ambient environmental quality conditions, and resources at risk,

The effects of coastal resource use on the biodiversity of United States coastal waters.

Increased knowledge in these areas will assure NOAA Fisheries and its partners a sound scientific basis for sustainable management of healthy coastal ecosystems.

Within the context of the goal to balance competing public needs and interests in the use and enjoyment of our living marine resources while preserving their biological integrity, there are several special problem areas that will be occupying much of our attention during the coming months and years. I want to bring a few of these special areas to your attention for consideration as you look at your research interests and opportunities and speculate what may be the critical management issues of the next Century for which managers will be needing good scientific advice.

Seal Populations and Interactions

Managers are in need of the best information possible on historical seal numbers and ranges and projections (based on current population growth and protection measures) as to what future population numbers and ranges may be. It appears possible that the increase in seal numbers may be leading to localized problems such as the presence of seals at the narrow mouths of seven rivers along the Maine coast where Atlantic salmon populations, proposed for listing under the Endangered Species Act, reside. In one of these rivers in particular, the Machias River, the majority of the salmon inspected had evidence of seal damage. With only a handful of salmon returning to each of these seven rivers the loss of a single returning adult to a seal poses a very real threat to the continued existence of that river population.

The increased abundance of seals is also posing a problem for the salmon net pen aquaculture industry. Seals approach cages and can scare the cultured stock resulting in them not feeding for a day or more which in turn can lead to health problems. Seals also frequently attack cages resulting in partial or total losses of salmon within a cage. Not only does this result in an economic loss to the grower but it provides an opportunity for interaction between cultured and wild Atlantic salmon. The genetic, health and environmental risk associated with such interaction have been identified as a major potential threat to the continued existence of wild Atlantic salmon.

In recent years seal populations have increased dramatically in numbers and expanded in range. As stocks of seals recover they are "reclaiming" historical habitat which leads to conflicts of use between seals, fishermen, aquaculturists and beach goers. In addition, many are speculating on a correlation between seal population growth and decline in commercial fish stocks.

Net Pen Salmon Aquaculture

This activity is related in some ways to the first issue in that the activities interact with seals and pose issues regarding the management of wild Atlantic salmon populations.

The key challenge to state and Federal managers is how to support and encourage an industry that cultures and harvests Atlantic salmon while protecting, conserving and rehabilitating wild runs of Atlantic salmon. To address that challenge we need to focus on areas and instances of interaction between the cultured and wild Atlantic salmon. Potential areas for further research are in the areas of genetics (interbreeding and stock identification), fish health, competition (for food, disruption of redds), and habitat (potential for water quality degradation). Effective measures to address these potential impacts can only be implemented if we have a clear understanding of the nature and effects of such interactions. And we need to explore mechanisms which might be deployed in an effort to minimize such interactions, be they the result of escapement by cultured fish from their pens due to storms or seal attacks on the pens or simply the result of sharing a common water body.

The Impact of Towed Gear on Ocean Bottom Habitat

This topic has been discussed among managers for some time and has the potential to become a significant issue as managers attempt to recover depleted stocks of fish. There are two sides to this issue; one is that the bottom is damaged and organisms are killed or injured by the gear, whereas the other is that the nutrients locked in the sediments are resuspended by the gear, and these nutrients then become the catalyst for plankton blooms, which in turn lead to greater diversity and abundance. Studies which are carefully designed and carried out which address this issue are needed to assist managers as they deliberate management measures that may include restrictions on the use of certain types of gear in areas and at certain times in the Gulf of Maine.

Aquaculture

From pen rearing of salmon and tuna to rearing of cod and flounder, aquaculture has gained the attention of numerous entrepreneurs and the fishing industry as an alternative to the harvest of wild stocks of currently depleted stocks of groundfish. NOAA Fisheries has provided nearly $6 million in grants in the past 2 years for aquaculture projects, and has supported additional research through NOAA's Cooperative Marine Education Research Programs at the University of Massachusetts, the University of Rhode Island, and Rutgers University. Researchers at the University of Maine have recently achieved remarkable results in raising cod. Other work on summer flounder is showing considerable promise, too. Most aquaculture projects are not short-term, and it may take many years for the young to be raised to harvestable size. Short-term funding only begins to touch on the problems and gives a preliminary indication of long-term success. Genetic variations may not show up for several generations. Aquaculture research should be long-term and cover all stages of the operation, from spawning to harvest, in order to be useful.

As we move forward in encouraging the expansion of ocean aquaculture, we can not ignore the inevitable conflicts and problems that will arise and begin now to identify them and develop a basic understanding of the causes and effects. As in the case of the pen culture of Atlantic salmon, much needs to be done with regard to genetics, disease, nutrition, reproduction and habitat requirements on the most likely of aquaculture candidate species. As managers we are going to be required to make decisions regarding the siting and size of facilities. Our decisions will hinge, in large part, on the answers provided to some of these questions and will ultimately determine the success or failure of the operations. The absence of good science will only serve to delay or impede the development and expansion of responsible, sustainable aquaculture.

It has not been my intention here to describe a priority of issues facing managers so much as to provide a sense of the nature of concerns and issues faced by NOAA Fisheries and, I suspect, other management/policy officials in the Region of the Gulf of Maine.

United States Army Corps of Engineers

William A. Hubbard

The United States Army Corps of Engineers, New England Division, is a multi-disciplinary federal organization that has been meeting the water resources needs of the six state New England region for over a century. These needs have been in the areas of flood damage reduction, flood plain information and management, navigation, shore protection, water supply, stream bank protection, recreation, fish and wildlife resources conservation, environmental restoration and environmental protection, as well as technical assistance in other water resources areas. The areas of research the Division has identified as a priority in the Gulf of Maine include:
1. techniques for establishing and monitoring significant ecological restoration features, such as eelgrass beds,
2. understanding the benthic processes that influence the region's aquatic dredged material disposal sites, and
3. a scientific prioritization of the most critical ecological restoration needs on a Gulf-wide scale of habitat deficits.

At the turn of the century, the demands for deep draft, coastal freighter access to the region's ports were being addressed by the New England Division. As the mid-century evolved, the safety and protection of New England businesses and residents from storm and flood damages became a Corps priority. As we enter the latter years of this century, societal needs for environmental restoration are being met by the Corps newest programs, those involving environmental restoration. Currently the Corps is identified as the federal engineering organization for flood damage reduction, commercial navigation and environmental restoration.

Techniques for Establishing and Monitoring Significant Ecological Restoration Features

In implementing its regulatory responsibilities, the Corps is increasingly responsible for water resources trade-offs that involve compensatory mitigation for loss of significant ecological functions. One of our pressing needs is to understand and implement submerged aquatic vegetation (SAV; e.g., eelgrass) restoration projects. As our knowledge of the value and distribution of this significant resource grows, it has become increasingly evident that the dredging and expansion of our navigation features will conflict with the protection and expansion of the SAV resources. New England Division requires scientific analyses of the technical feasibility and cost effectiveness of eelgrass restoration and creation projects.

Understanding the Benthic Processes that Influence the Region's Aquatic Dredged Material Disposal Sites

The area of dredged material management has many scientific issues of concern. An analysis of the risk associated with leaving contaminated sediments in our harbors, in comparison to dredging and disposal impacts is an important issue of concern. A level of acceptable risk, models of impacts and regional monitoring may all be required. The New England Division needs an investigation of the contaminant losses during disposal of dredged sediments. Existing literature and a well designed series of studies in the northeast may provide some answers in this arena. Investigations need to be conducted in-situ to determine the factors that result in sediment deposits becoming more resistive to erosion than theoretical predictions. Additionally, there is a need to develop a much less expensive approach to assessing the adverse impacts of sediment contaminants. An inexpensive screening test, akin to litmus paper, is needed to expand the spatial distribution of sediment characterization in New England (e.g., expanded microtox testing).

A Scientific Prioritization of the Most Critical Ecological Restoration Needs

There is a critical need to protect and improve the ecological productivity of the Gulf of Maine. The New England region has been extensively influenced by the development of its water resources to meet the needs of a growing population. The coastal zone in the Gulf of Maine region, in particular, is densely populated with this trend projected to continue into the 21st century. The infrastructure developments since the turn of the century (e.g., the transportation corridors, navigation features and flood control structures) have produced systematic changes in the ecological productivity of the New England landscape, many of which were unforeseen and until recently, were not even noticed.

The Northeast Regional Implementation Team of the Coastal America partnership several years ago defined the most important ecological restoration priorities in New England as being the restoration of saline tidal flow into coastal salt marshes and the restoration of anadromous fisheries migration to modern historic spawning grounds. These two efforts are focused on species of national priority. The collapse of the commercial fisheries industry in New England, has highlighted that many species, particularly anadromous fisheries are dependent on wetlands and migration corridors within their life cycles. Accordingly, wetlands restoration efforts are considered a national economic development priority.

The reduction of saline tidal exchange in coastal New England marshes has allowed soils to lose their salinity over the numerous decades of man made impacts. The result is a change in the flora and a shift in the fauna as monospecific stands of the woody reed *Phragmites* dominate these formerly productive wetlands. Many sites in New England are now very low in ecological value because of the loss of their *Spartina* spp. dominance. The larger marshes (many several hundred acres in size), numerous anadromous fisheries impasses, along with the thousands of smaller sites with a variety of ecological degradation problems, need to be examined and ranked as to their ecological restoration priorities. Additionally, the ecological scientific community needs to inform the decision makers of the ranking of importance for all potential environmental restoration opportunities in New England. This will prioritize the expenditure of funds toward projects that obtain the highest ecological benefits per expenditure.

The New England Division assists in meeting national, regional and local water resource needs through a variety of programs. Congressionally authorized water resources investigations have resulted in the planning, design and implementation of many flood control and flood damage reduction measures and deep and shallow draft navigation improvements, as well as significant ecological restoration projects. Increased scientific knowledge in the aforementioned areas will support the long-term implementation of the Corps mission in New England.

United States Environmental Protection Agency

Philip Colarusso

The three issues that we have identified as research priorities for the Gulf of Mane are not unique to the Gulf of Maine, but are also national issues. They are as follows:

Subtidal Habitat Loss and Degradation

Over the last 15-20 years, we've been doing a good job of protecting emerged wetland habitat, but have only recently within the last several years been more aggressive about protecting submerged habitats. Much of the basic information that EPA needs as a regulatory agency for decision-making is only now becoming available. Comprehensive habitat maps such as generated by the National Wetlands Inventory Program do not yet exist for submerged marine systems. Some important pieces of information that are needed for such a comprehensive effort already exist or are in the process of being developed. For example, the U.S. Geological Survey has collected vast amounts of bathymetry and sediment type data for Massachusetts and Cape Cod Bays. This information should serve as the foundation which biological information can be built upon. Currently, the States of Maine and Massachusetts and the University of New Hampshire have mapped eelgrass using aerial photographs. State shellfish programs have information on shellfish bed locations. Additional mapping efforts need to be carried out for other important marine habitats such as kelp beds or macroalgae. The bulk of the effort to date has been in the nearshore environment, which does constitute less than 1% of the surface area of the Gulf of Maine. Nearshore environments do face a wider array of anthropogenic threats than offshore environments do. Though the majority of work for a number of years will continue to be within the nearshore environment, we cannot afford to ignore the offshore areas completely.

Management of Contaminated Sediments

Nationally, the management of contaminated sediments is a technically challenging and economically costly issue. As the shipping business continues to move to deeper draught vessels, the need for dredging increases. The latest class of cargo ships coming off the construction line will require 45 feet of water for navigation. The new double-hulled supertankers will require 50 feet of water. No port in new England could currently handle either of these vessels on most stages of the tide. Unfortunately, we are now paying for past sins of poor waste water treatment, combined sewer overflows (CSOs), storm water runoff, etc. It is not just urban ports that face this issue. It is an issue that many small marine owners and communities face as well. Boats themselves can be significant sources of pollutants from fuel oil to antifouling paints. Many New England harbors now have record numbers of boats in them and as a result have high levels of petroleum hydrocarbons and other contaminants in their sediments. Prohibiting dredging is not a option, but the thoughtful management of this type of material is essential. Research that would lead to better management of this material is crucial.

Effects of Nitrogen on Gulf of Maine

The Gulf of Maine does not experience the low dissolved oxygen levels that plague Long Island Sound, but it is possible that nitrogen is having more subtle impacts. Is the Gulf experiencing more widespread nuisance algal blooms than in the past and if so, how does nitrogen factor in to this? Have red tide, *Ulva*, and other species spread and if so what role has nitrogen played? Recent articles in the New York Times point to a global increase in nuisance algae blooms, with excess nitrogen being blamed as a contributing factor. These nuisance algal blooms can have severe environmental and economic effects. Red tide can close shellfish beds for harvesting for extended periods and has been implicated in causing fatalities in a number of endangered marine mammals. Brown tides and green algae species such a *Ulva* have been shown to overrun and replace nearshore habitats such as eelgrass. These nuisance species have been shown to form a less desirable habitat for fish and invertebrates than the habitats they have replace. Better information on the role nitrogen is playing in the proliferation of these nuisance algal species and documenting their full range of impacts is needed. Prior to any targeted control, an inventory estimating the various major sources of nitrogen would be needed.

EPA has been funding research into these important areas both regionally and nationally. EPA's three National Estuary Programs that fall within the Gulf of Maine have contributed significant funding to each of these issues. As an agency, we will continue to provide our expertise and funding to issues such as these.

Physical Oceanography of the Gulf of Maine: An Update

Robert C. Beardsley
Woods Hole Oceanographic Institution
Bradford Butman
U. S. Geological Survey
W. Rockwell Geyer
Woods Hole Oceanographic Institution
Peter Smith
Bedford Institute of Oceanography

Introduction

Since the last Gulf of Maine Symposium (Wiggins and Mooers, 1992), there have been significant advances in our understanding of the physical oceanography of the Gulf of Maine system. This understanding is a result of extensive new field studies and significant advances in modeling. Coupled field and modeling studies, each providing a unique perspective on this complex system, have been especially fruitful. In addition, the Gulf of Maine scientific community is beginning to provide data and interpretations electronically over the World Wide Web, facilitating the exchange of data and synthesis. Studies have been motivated by the opportunity to document and understand fundamental physical processes and global change in this complex coastal system, as well as by the regional importance of the Gulf of Maine.

New Field Studies

Significant new field programs have been undertaken in the 1990s to look at a variety of physical processes within the Gulf of Maine (Tables 1 [page 40] and 2 [page 41], Figure 1 [page 42]). Many of these physical oceanographic studies are parts of larger interdisciplinary programs, designed to look at ecosystem questions ranging from near shore water quality issues around the rim of the Gulf of Maine to the early life history of cod and haddock on Georges Bank. The field studies have often utilized new instrumentation that measure a wide range of physical, biological and chemical parameters with vastly improved resolution in space and time; this increased resolution has greatly improved basic descriptions of the distributions of properties, as well as provided insight to generate new hypothesis. Some principal results, emphasizing the basin-scale general circulation and those physical processes which influence its variability, include:

1. The Gulf of Maine is an integral part of the northeastern North America coastal ocean circulation system. Oxygen isotope measurements indicate that mean flow in the Scotian Shelf/Gulf of Maine/Mid-Atlantic Bight is part of a long, leaky, primarily buoyancy-driven coastal current which carries fresh water from a variety of sources in the northern Labrador Sea and continental runoff southward to Cape Hatteras (Figure 2 [page 43]) (Loder et al., 1996).
2. The Gulf of Maine has a distinct estuarine character, with relatively fresh water entering from the Scotian Shelf, where local runoff and precipitation mix with salty slope water entering through the Northeast Channel to produce water of intermediate salinity which flows westward alongshelf and offshelf (Figure 3 [page 44]). Past estimates of volume and freshwater transports through the Halifax and Nantucket Shoals sections need reconsideration, based on (a) new ideas about the structure and strength of the Scotian Shelf inflow (Smith and Schwing, 1991; Han et al., 1996), (b) quantitative estimates of offshelf transport by warm-core rings (Joyce et al., 1992; Schlitz, 1996), and (c) direct measurements of the strength of the shelfbreak jet (Gawarkiewicz et al., 1996).

Table 1.
Gulf of Maine Physical Oceanographic Programs (1991-96)

Description and Objectives	Principle Investigators
Massachusetts Bays Program: Develop understanding of circulation and physical mixing processes in Mass. and Cape Cod Bays, as part of a larger program to predict environmental effects caused by moving the location of the Boston sewage outfall from Boston Harbor to western Mass. Bay. Moorings, hydrographic surveys, drifters; 1990-91. Long-term monitoring: moorings, hydrographic surveys; 1989-present.	R. Geyer, B. Gardner, R. Signell, W. Brown, B. Butman
Mass. Bay Long-term Monitoring Program: Document suspended sediment transport on event, seasonal, and interannual time scales in Massachusetts Bay east of Boston Harbor. Long-term moorings, time-series sediment traps; 1989- present.	R. Signell, M. Bothner, B. Butman
Western Gulf of Maine Red Tide Study: Understand behavior of the Kennebec River plume during late spring-summer and its role in the transport of toxic 'red tide' algae along the western Gulf of Maine rim. Moorings, hydrographic/ADCP surveys, drifters; March-July, 1993 and 1994.	D. Anderson, R. Geyer, T. Loder, R. Signell
Mass. Bay Vertical Mixing Study: Measure vertical diffusion in the seasonal pycnocline in Massachusetts Bay and compare with other vertical mixing processes. Hydrographic and dye-tracking surveys; July 1993 and July 1995.	R. Geyer, J. Ledwell
Jordan Basin Circulation Study: Document and understand the circulation in the northeast Gulf of Maine with focus on the Maine Coastal Current. Moorings, hydrographic surveys, drifters; April 1994-present.	N. Pettigrew
Western Gulf of Maine Circulation Study: Understand the coupling between Wilkinson Basin circulation and the western Gulf of Maine coastal current. Moorings, hydrographic surveys: spring/summer 1994 and 1995.	W. Brown, F. Bub
U. S. GLOBEC/Georges Bank Study:	
A. 1995 Stratification Study: Document and understand physical processes which control the circulation and stratification of shelf water over Georges Bank, with focus on the winter-to-summer period over the northeastern and southern flank. Moorings, hydrographic/ADCP surveys, drifters; February-August 1995.	B. Beardsley, J. Churchill, D. Hebert, S. Lentz, J. Manning, D. Mountain, N. Oakey, B. Weller, S. Williams
B. Long-Term Measurements: Measure and characterize water properties and Eulerian and Lagrangian currents over Georges Bank, with focus on the eastern and southern flank, throughout five-year life of GLOBEC field program. Long-term moorings, bank-wide hydrographic/ADCP surveys, drifters; November 1994-present.	B. Beardsley, J. Bisagni, K. Brink, J. Candela, C. Flagg, J. Irish, D. Limeburner, D. Mountain
C. Gulf of Maine Inflow Study: Monitor the inflow of Scotian Shelf Water and Slope Water into the eastern Gulf of Maine. Long-term moorings,hydrographic/ ADCP surveys; October 1993-present.	P. Smith
Gulf of Maine Internal Wave Experiment: Examine the role of tidally generated internal wavepackets on vertical mixing and transport of nutrients across seasonal pycnocline. Moorings, hydrographic/ ADCP surveys; August 1995, June-Sept. 1996.	D. Townsend, N. Pettigrew, P. Brinkley, J. Wallinga, F. Chai, A. Thomas, C. Yentsch, M. Sieracki, C. Garside, D. Phinney, J. Brown
Western Gulf of Maine Convective Mixed Layer Deepening Study: To document winter cooling-induced convective mixed layer deepening and understand its role in water mass formation. Moorings, hydrographic/ADCP surveys: January-March 1997, October 1997-May 1998.	W. Brown, F. Bub

Table 2.
Estuarine Physical Oceanographic Studies in the Gulf of Maine (1991-96)

Description	Principle Investigators
Circulation and Flushing Study of Casco Bay: Characterize the spring and summer hydrography of Casco Bay and the Sheepscot and Kennebec estuaries, and examine the tidal and residual circulation of the bay using a numerical model. Hydrographic surveys: July-August 1992; April 1993.	B. Pearce, N. Pettigrew
Comparative Study of the Kennebec, Sheepscot and Damariscotta Estuaries: Seasonal characterization of hydrography, circulation, nutrient budgets, and productivity of three adjacent estuaries that differ one from another by successive orders of magnitude of freshwater input. Hydrographic, current, nutrient, geo-chemical, and light surveys: September 1993; February, May, June, July, August, September 1994; September 1995.	L. Mayer, T. Loder, C. Newell, N. Pettigrew, D. Townsend
Study of exchange processes between the Kennebec River estuary, Casco Bay, and the inner shelf: implications for Red Tide and contaminant transport: Detailed measurements of tidally averaged hydrographic and current fields in the Kennebec, outer Casco Bay, and the connecting inner shelf under spring freshet and summer conditions during 1997 and 1998. Hydrographic and ADCP surveys; spring and summer. 1997-1998.	N. Pettigrew, M. Keller
Vernal Circulation Study of Penobscot Bay: Document the subtidal spring circulation pattern of the bay. Moorings, hydrographic/ADCP surveys: February, April, June 1997.	N. Pettigrew

3. The Gulf of Maine circulation is strongly influenced by topography, with clockwise flow over Browns (Smith, 1989b) and Georges Banks and Nantucket Shoals (Figure 4 [page 45]) and counterclockwise flow over Jordan, Wilkinson, and Georges Basins (Brown and Irish, 1992; Bisagni and Pettigrew, 1994). The Northeast Channel is only a partial barrier to the "cross-over" of Scotian Shelf water from Browns to Georges Bank (Figure 5 [page 46]) (Williams, 1995; Bisagni et al., 1996).

4. The Gulf of Maine circulation and water property fields vary on wide range of time and space scales. Strong tidal currents over Georges Bank generate (a) strong turbulent mixing in the bottom boundary layer (Yoshida and Oakey, 1996; Werner, 1996) and (b) large amplitude internal waves on the flanks of the bank and in Wilkinson Basin (Loder et al., 1992; Irish, personal communication; Townsend et al., 1996). Strong wind events can generate strong currents over Georges Bank (e.g., maximum hourly currents of 1.1 m/s measured in the upper water column over the southern flank during hurricane Edouard [Irish, personal communication]). Other episodic forcing events for Georges Bank include shelf–slope interactions (e.g., Slope Water intrusions [Figure 6, page 47], shelf water entrainment by warm-core rings [Figure 7, page 48]) and Scotian Shelf "cross-overs." Inflows into the Gulf of Maine exhibit distinct seasonal variations (Smith, 1983, 1989a), with the basin-scale heat content dominated by the seasonal cycle of the regional surface heat flux and the salt budget dominated by the upstream flux of fresh water (Mountain, 1991; Manning, 1991; Mountain and Manning, 1994; Mountain et al., 1996). Interannual variability in surface and upstream forcing (Smith, 1989a), together with wide variations in the number of warm-core rings along the Gulf of Maine seaward boundary and the character of their interaction with the shelf, combine to produce significant year-to-year variation in circulation and water property distributions.

5. The Gulf of Maine coastal current flows around the margin of the Gulf and is a boundary and transport pathway between the nearshore and offshore. Along the

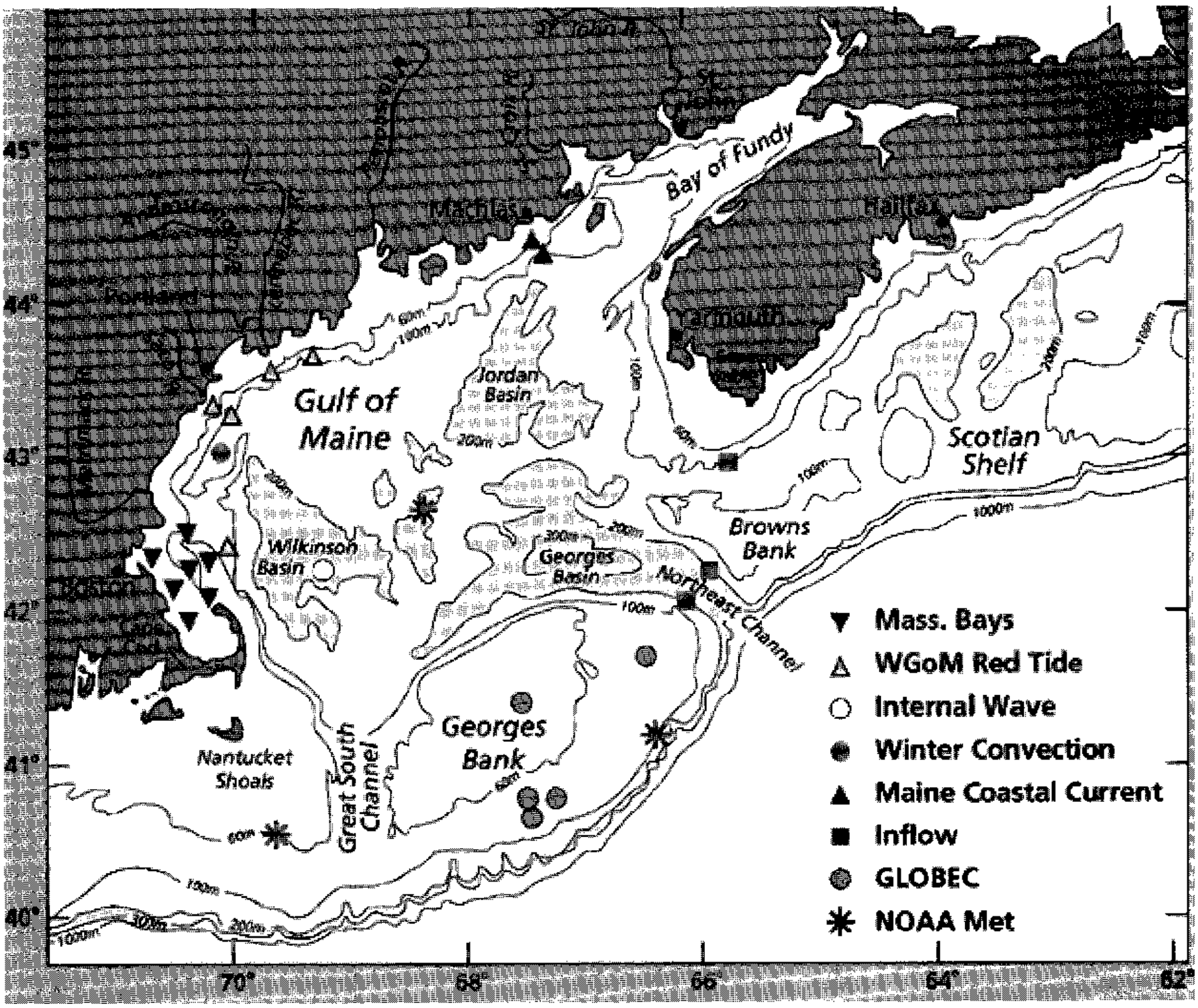


Figure 1. Approximate locations of moorings deployed in physical oceanographic field programs being conducted in the Gulf of Maine during the 1990's. See Tables 1 and 2 for list of programs. Also shown are locations of the three NOAA environmental buoys deployed in the Gulf of Maine.

western Gulf of Maine, it flows southwestward, driven principally by upstream buoyancy, as well as local inflow from rivers. The structure of the current varies considerably due to river runoff and wind. It apparently branches offshore at several locations, forming a "leaky" alongshore transport system as well as a mechanism for transporting water and material offshore. The Maine Coastal Current can feed both the Jordon Basin gyre and the coastal current which extends around the western rim of the Gulf of Maine to the Great South Channel (Figure 8, page 48) (Pettigrew et al., 1996; Geyer, personal communication). Along the western Gulf of Maine, the current transports Alexandrium Tamaranse, a toxic dinoflagelate, from a source region in Penobscot Bay, southward along the NH and MA coasts.

(Text continues on page 49)

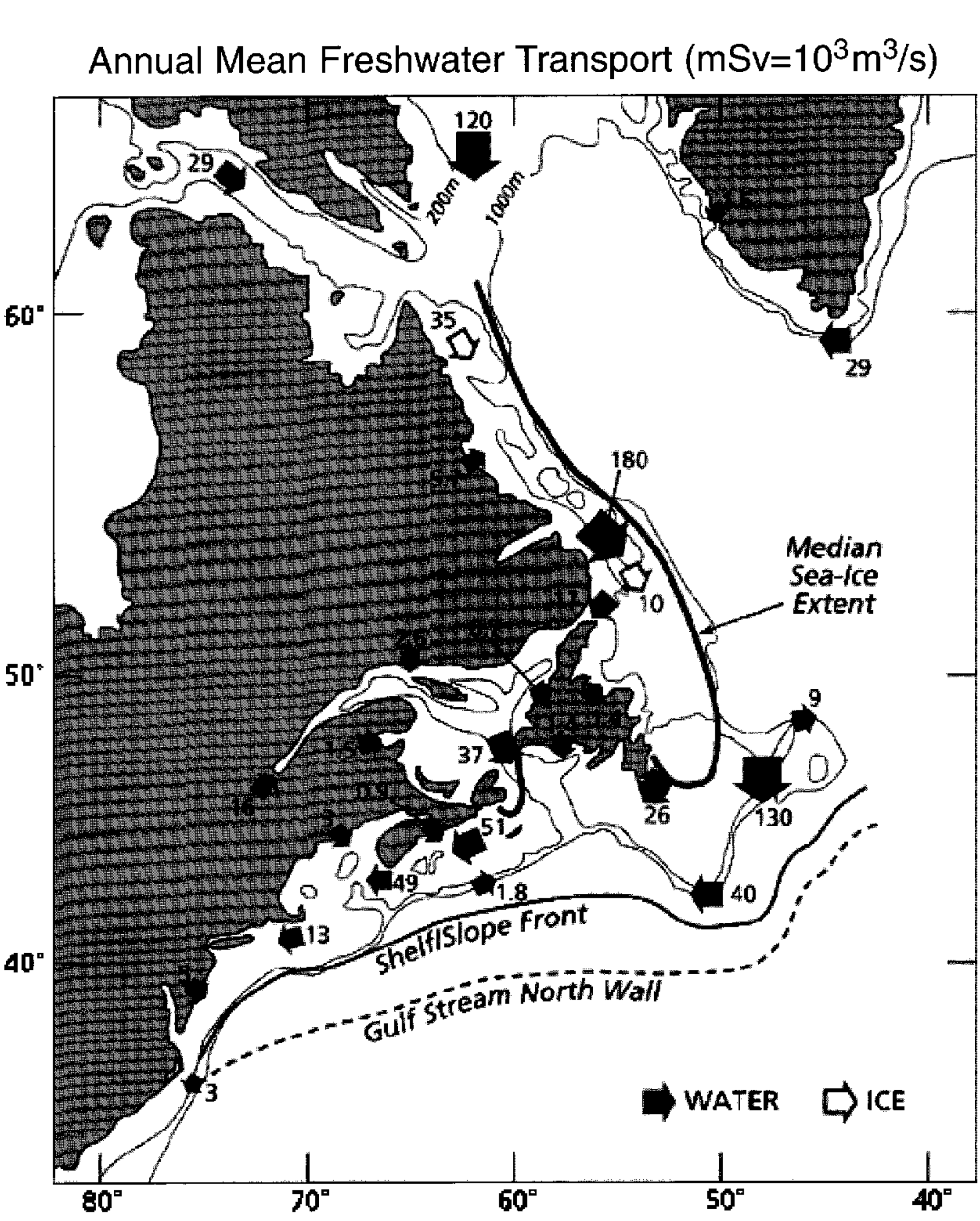


Figure 2. Schematic of annual mean freshwater transport along northeastern margin of North America. These estimates based on long-term moored array, repeated hydrographic sections, and river discharge data. (Figure redrawn from Loder et al., 1996.)

General Circulation During Stratified Season

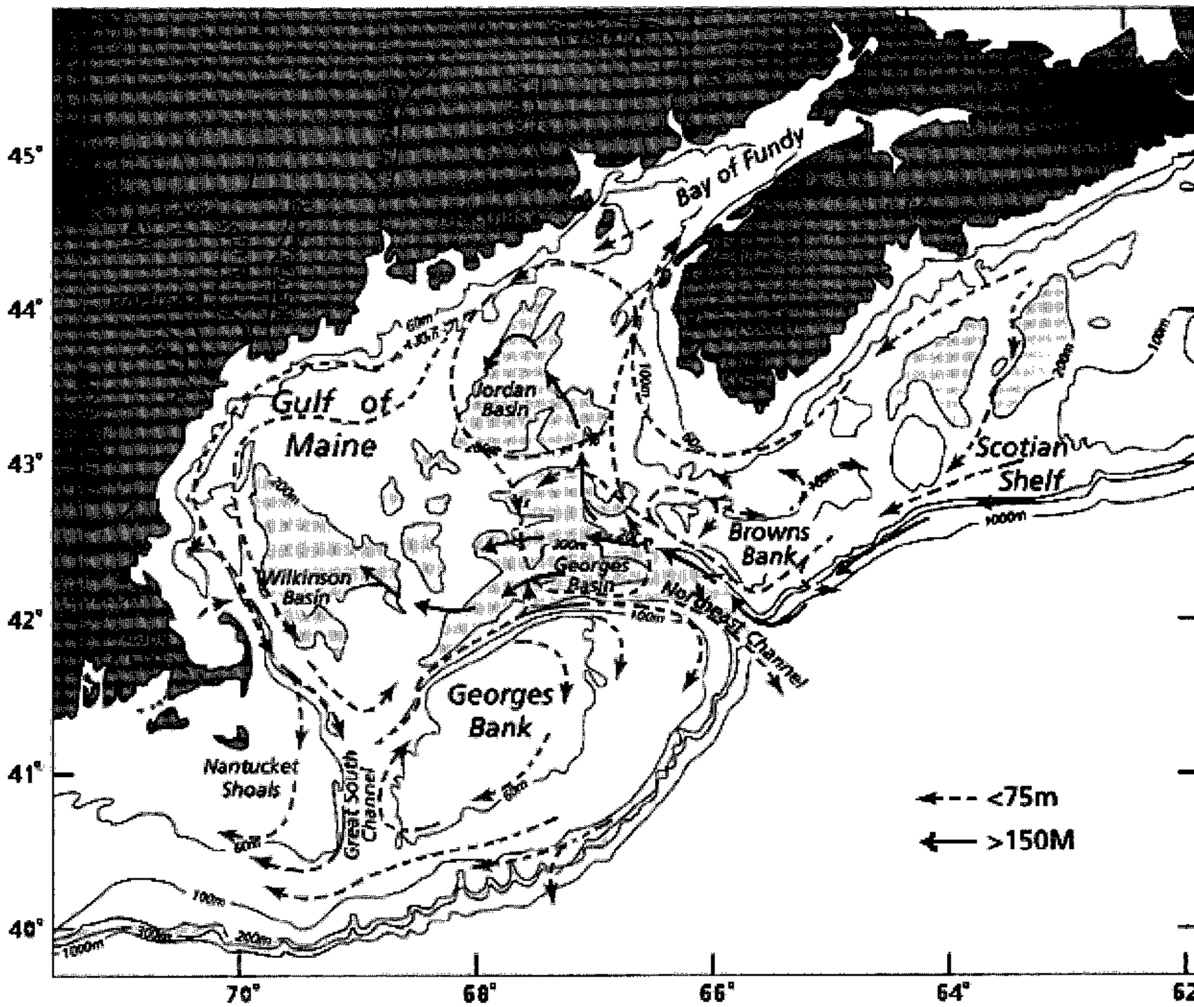


Figure 3. Schematic of upper and lower layer circulation in the Gulf of Maine during the stratified season based on most recent moored, hydrographic and drifter data. (N. Pettigrew and R. Geyer contributed to this update of Brooks' 1985 schematic.)

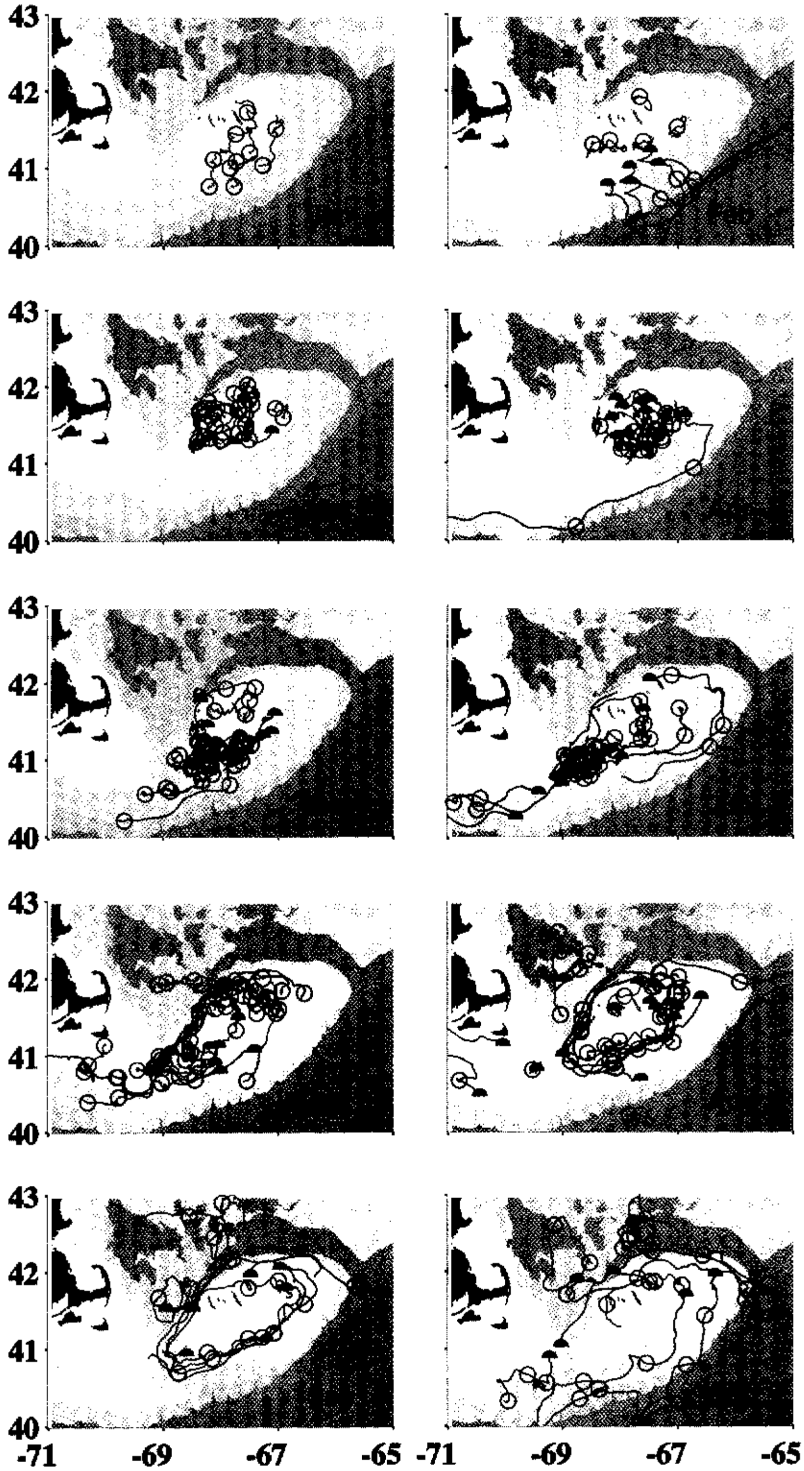


Figure 4. Trajectories of satellite-tracked drifters drogued at 10 m deployed in 1995 over Georges Bank as part of the U.S. GLOBEC/Georges Bank program. The tracks have been low-pass filtered to remove tidal motion and plotted by month. (Figure supplied by R. Limeburner.)

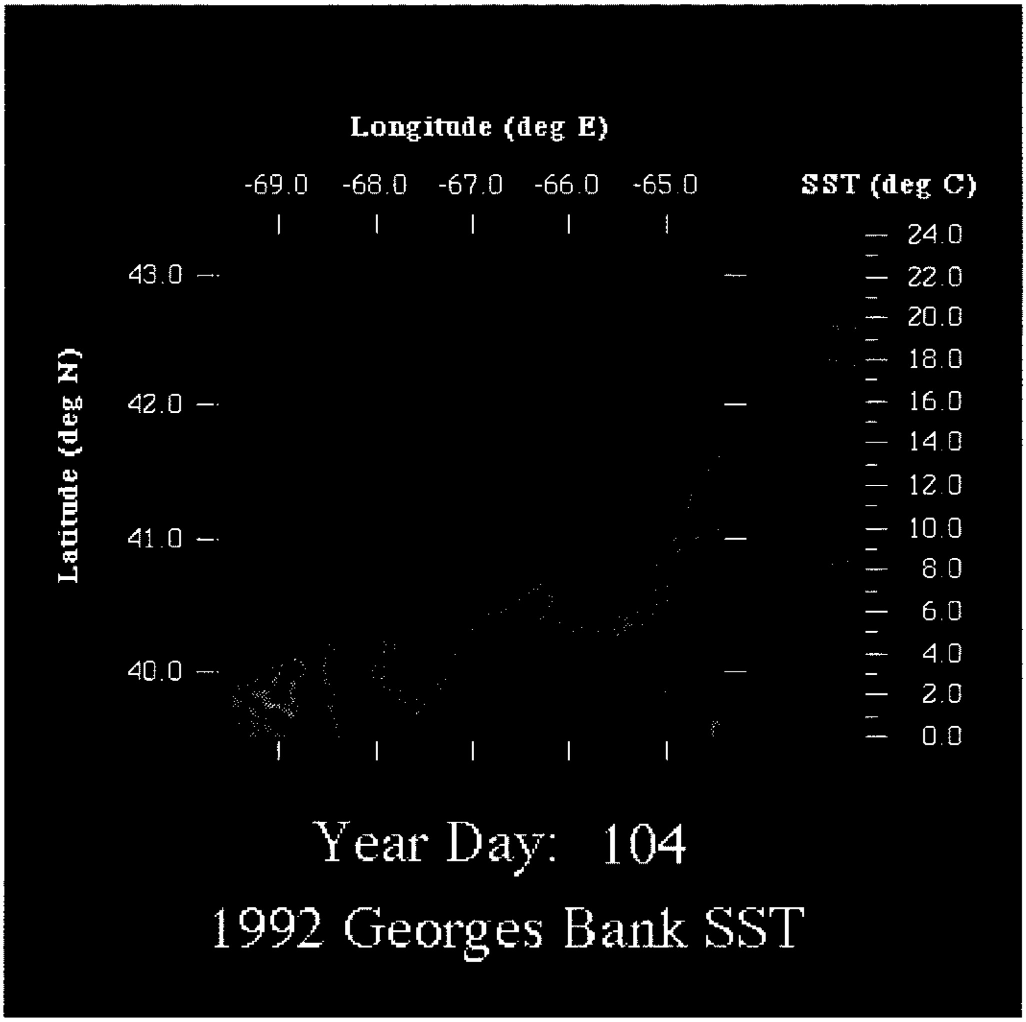


Figure 5. Map of Sea Surface Temperature on April 11, 1992 showing the "cross-over" of cold Scotian Shelf water from the southeastern edge of Browns Bank over the Northeast Channel and onto the eastern end of Georges Bank. (Figure supplied by J. Bisagni.)

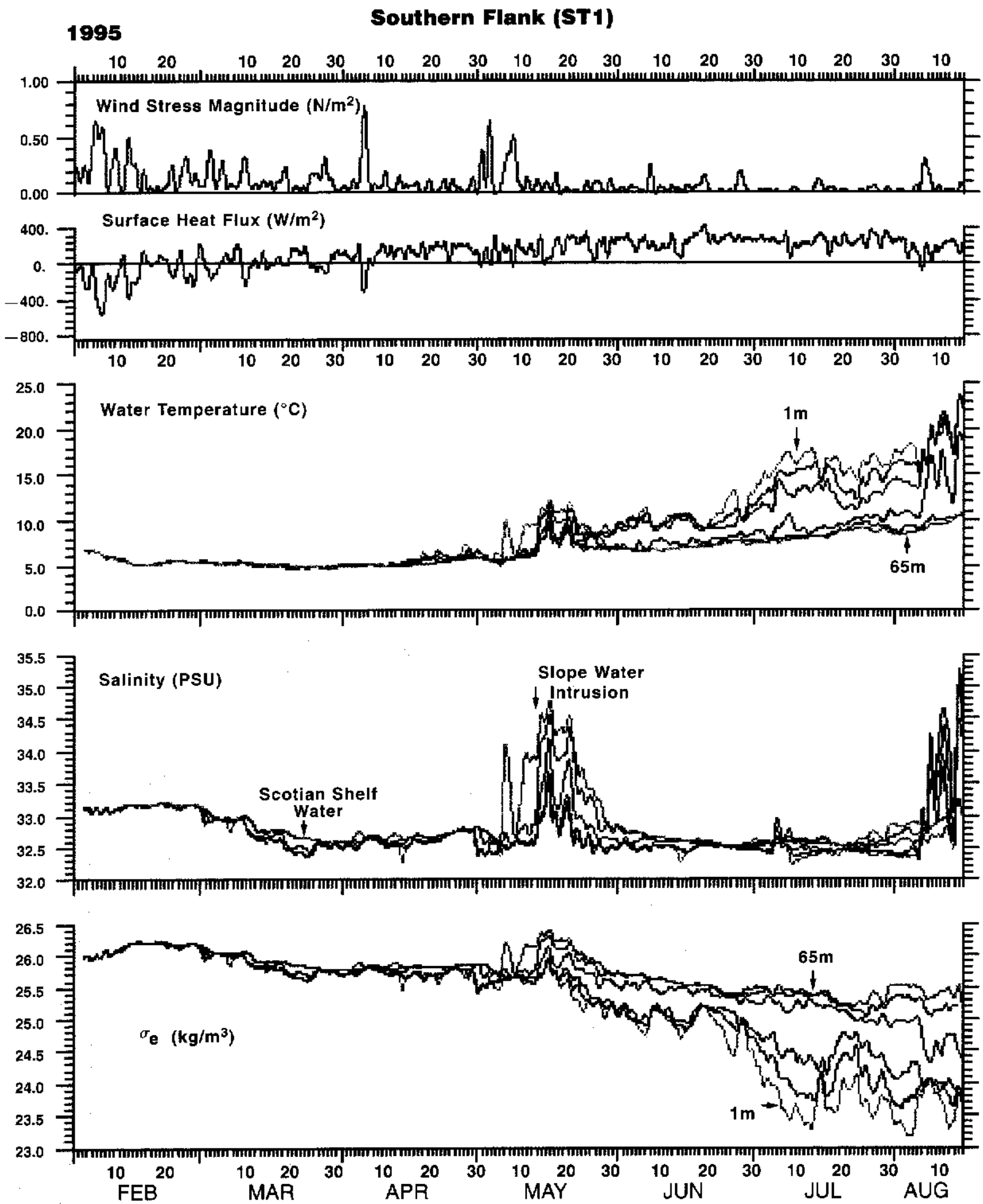


Figure 6. Time series of wind stress magnitude, surface heat flux, water temperature, salinity and sigma-theta measured at the GLOBEC ST1 site 40.86°N, 67.56°W) on the southern flank of Georges Bank. The water property variables are computed from in-situ measurements of temperature and conductivity at six depths which approximately span the 76-m water column. Note the passage of a small parcel of Scotian Shelf water in March and the major intrusion of Slope Water in May. (Data collected by R. Beardsley, S. Lentz, and R. Weller.)

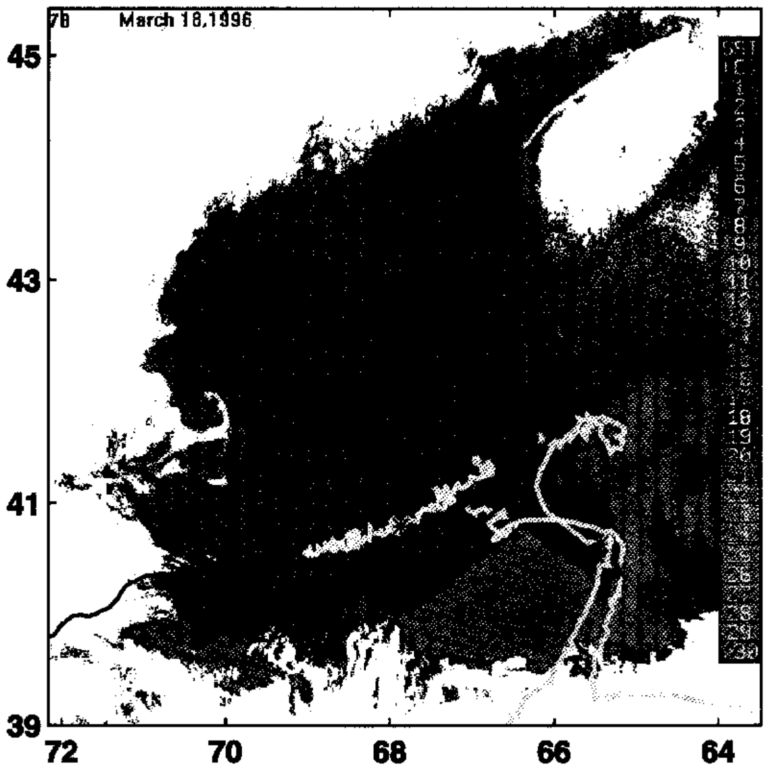


Figure 7. Map of Sea Surface Temperature on March 18, 1996 with drifter trajectories superimposed showing the entrainment of shelf water from the outer shelf around a warm-core ring centered near 66.5°W, 39.7°N. The drifter tracks are plotted for a 20-day period with the center day corresponding to the date of the Sea Surface Temperature map and denoted by the solid circle on the track. Note that the drifter located over the mid-sheld was not entrained. (Figure supplied by R. Limeburner.)

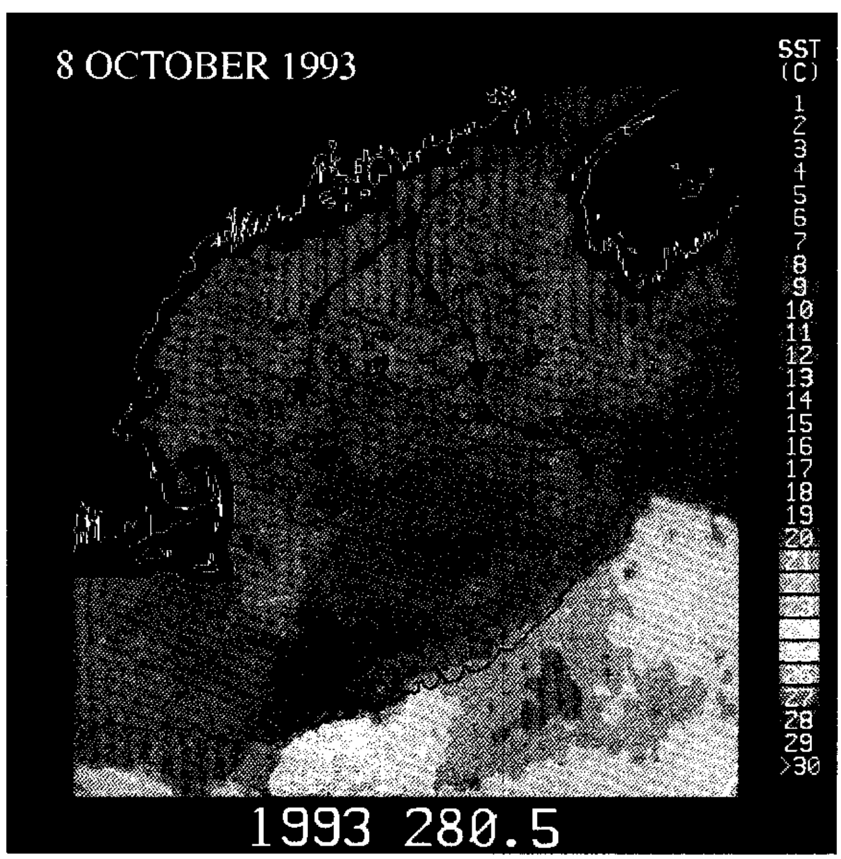


Figure 8. Map of Sea Surface Temperature on October 8, 1993 showing the path of Maine Coastal Current water suggested by Sea Surface Temperature, hydrography, and drifter measurements. (Figure supplied by J. Bisagni.)

Table 3.
Gulf of Maine Physical Oceanographic Model Studies (1991-96)

Description	Principle Investigators
Numerical study of circulation in Passamaquoddy Bay and the Bay of Fundy	D. Greenberg, F. Page
Modeling the circulation in Cobscook Bay	D. Brooks, Y.-T. Lo
Numerical modeling of Maine Coastal Current in spring	M. Holboke, D. Lynch
Western Gulf of Maine Red Tide Study Develop idealized and realistic physical and phytoplankton model to predict spread of toxic 'red tide' algae from Kennebec River along western Gulf of Maine rim	R. Signell, D. Anderson, D. Fong, R. Geyer, B. Keafer, T. Loder
Massachusetts Bays Program Develop realistic physical circulation and water quality model to predict environmental effects associated by moving Boston sewage outfall to western Massachusetts Bay. New focus is to predict sediment transport.	R. Signell, A. Blumberg, H. Jenter
Simulation of Outfall Plume Characteristics Using a Far-Field Circulation Model	X. Zhang, E. Adams
U. S. GLOBEC/Georges Bank Study Develop better understanding of physical processes which govern circulation and water property evolutionand influence phytoplankton and zooplankton distributions during winter-to-summer transition.	
A. Idealized Process-Oriented Studies	C. Chen, C. Davis, G.Flierl, P. Franks, G. Gawarkiewicz, S. Werner, B. Williams
B. Realistic Domain Studies	C. Davis, W. Gentleman, D. Greenberg, D. Haidvogel, C. Hannah, J. Loder, G. Lough, D. Lynch, D. McGillicuddy, C. Naimie, C. Werner
Effects of Drilling Wastes on Georges Bank Scallop Populations	D. Gordon, C. Hannah, J. Loder, T. G. Milligan, K. Muschenheim
Inverse Gulf of Maine Circulation Modeling	F. Bub, W. Brown.
Biological Modeling of the Gulf of Maine Develop a gulf-wide circulation and biological model to assess the annual nutrient budget and the annual cycle of plankton distributions	H. Xue, F. Chai, N. Pettigrew, D. D. Campbell, C. Pilskaln
Idealized Modeling of the Shelfbreak Jet and its Bottom Boundary Layer Dynamics	D. Chapman, S. Lentz
Idealized Study of Shelf-Slope Frontal Instabilities	M. Spall
Model study of shelf-slope coupling	Q. Sloan, A. Robinson

Modeling

New computer technologies have allowed major advances in modeling of the circulation and physical processes in the Gulf of Maine. In coastal systems such as the Gulf of Maine that have complex geometry and bathymetry, and where multiple agents (such as wind, tide, river runoff, heating and cooling, and the adjacent deep ocean) drive the currents, the spatial and temporal variability often cannot be adequately resolved by field measurements alone; models have provided insight into the spatial and temporal complexity of processes that have complemented the new field measurements. Companion field and model studies have provided a unique mechanism to advance understanding of the Gulf of Maine system in a way not possible five years ago.

Many new circulation modeling efforts, ranging from idealized, process studies to realistic simulations, have been initiated (Table 3). Some of these studies, especially those featuring realistic domains, have been closely linked with field programs, so that boundary conditions may be better estimated and results tested by detailed model-data comparisons. One of the principal efforts has been a comprehensive finite-element primitive equation circulation model for the Scotian Shelf/Gulf of Maine/eastern Mid Atlantic Bight domain, developed by D. Lynch and coworkers at Dartmouth College (Lynch et al., 1996). This effort has lead to a sequence of model studies to understand the influences of offshore tidal, surface and density forcing on the seasonal circulation, as well as simple tropodynamic models for exploring the distributions and biophysical interactions of zooplankton and larval fish. Other new initiatives include work on data assimilative models for the Gulf of Maine, and an effort to embed the Dartmouth finite-element model within a North Atlantic circulation model, to eliminate open boundary problems and provide more realistic simulations of slope processes such as warm-core ring interactions with shelf waters.

Electronic Communication and Data Distribution

Significant improvements in electronic communication (e.g., data display including movies/ simulations via Internet) and distributed data archives (available via anonymous FTP or Internet) have also facilitated better scientific exchange within the Gulf of Maine community. Efforts have focused on providing key historical and real time data sets as well as descriptions of on-going studies over the network through a distributed system. Over the long term, the goal is to build a digital information bank for the Gulf of Maine that can be easily by expanded to include new data and information. Three examples of these data and information web sites are:

1. The U. S. GLOBEC Georges Bank World Wide Web site (http://globec.whoi.edu/) where descriptions of the Georges Bank program can be found along with a comprehensive archive of data and data products (e.g., animated drifter tracks);
2. A pair of complementary marine data and information management systems for the Gulf of Maine named REDIMS (http://oracle.er.usgs.gov/gomaine/) and EDIMS (http://rossby.unh.edu/edims/edims.html) (Brown and Garrison, 1996);
3. J. Bisagni's World Wide Web site (http://kraken.gso.uri.edu/bisagni.html) where optimally interpolated SST maps are stored.
4. The Gulf of Maine Council on the Maine Environment web site (http://www.gulfofmaine.org) (under Data & Information section)

Summary

The new field and model studies are providing exciting new insights into the physical oceanography of the Gulf of Maine. Notable achievements in the last five years include:

1. Major new field experiments designed to increased understanding of the basin-scale circulation and the coupling between biological and physical processes;
2. Improved documentation of the distribution in space and time of physical, biological and chemical parameters at small spatial scales, made possible by new sampling technologies and strategies;
3. Development and implementation of numerical models that provide unprecedented resolution of physical fields in space and time; when coupled with field observations, these models have provided a unique mechanism to advance understanding of the Gulf of Maine system in a way not possible five years ago.
4. Distribution of data and information over the World Wide Web, facilitating research activities between scientists, as well as wide distribution of information to the Gulf of Maine community.
5. Continued exchange and coordination between researchers investigating the Gulf of Maine.

In the next five years we anticipate:

1. Significant progress in documenting the understanding of the large-scale circulation in the Gulf of Maine, and in the coupling of physical and biological processes.
2. Expanded use of models in companion field/model studies, increased hindcast studies, and improvements in data assimilation in large-scale numerical circulation model, and beginning attempts at real-time forecasting.
3. Investigations of the coastal current in the Gulf of Maine, and its role in the transport of water and material alongshore and offshore.
4. A new scientific synthesis of the Gulf of Maine, perhaps built upon the present efforts on the World Wide Web, that can be easily updated and widely distributed.

The opportunity to study the wide range of processes in the Gulf of Maine system continues to challenge and excite the international scientific community located around its border. Given the high level of field and theoretical research presently underway and anticipated for the next five years, we can expect continued progress in understanding the physics of this unique coastal system.

Acknowledgments

The authors want to thank J. Bisagni, W. Brown, J. Churchill, G. Gawarkiewicz, J. Irish, S. Lentz, R. Limeburner, J. Manning, C. Naimie, N. Pettigrew, R. Signell for their contributions to both the symposium talk and this summary. B. Connolly, J. Cook, C. Alessi, and A.-M. Michael helped with graphics and final preparation. Support for this work was provided by NSF (RB), the USGS (BB), NOAA (RG), and BIO (PS).

References

Backus, R. H., and D. W. Bourne, eds. 1987. *Georges Bank.* Cambridge: MIT Press, 593 pp.

Bisagni, J. J., N. R. Pettigrew, K. W. Seemann, and R. Hetland, 1995. Mesoscale structure in the northern Gulf of Maine, Fall 1993–Summer 1994. Proceeding of the Fourth Meeting of The Oceanography Society, April 18–21, 1995, Newport, RI, p. 72.

Bisagni, J. J., R. C. Beardsley, C. M. Ruhsam, J. P. Manning, and W. J. Williams, 1996. Historical and recent evidence concerning the presence of Scotian Shelf Water on southern Georges Bank. *Deep Sea Research,* (GLOBEC Special Issue), 43:1439-1471.

Brooks, D. A., 1985. Vernal circulation in the Gulf of Maine. *J. of Geophysical Research,* 90:4687–4705.

Brown, W. S., and J. D. Irish, 1992. The annual evolution of geostrophic flow in the Gulf of Maine: 1986–1987. *J. of Physical Oceanography,* 22:445–473.

Brown, W. S., and K. M. Garrison, 1996. A pair of complementary marine data and information management systems for the Gulf of Maine, (this volume).

Gawarkiewicz, G., T. G. Ferdelman, T. M. Church, and G. W. Luther, 1996. Shelfbreak frontal structure on the continental shelf north of Cape Hatteras. *Continental Shelf Research,* 16:1751-1773.

Han, G., C. G. Hannah, J. W. Loder, and P. C. Smith, 1996. Seasonal variation of the three-dimensional mean circulation over the Scotian Shelf. *J. of Geophysical Research,* submitted.

Joyce, T. M., J. K. Bishop, and O. B. Brown, 1992. Observations of offshore shelf-water transport induced by a warm-core ring. *Deep Sea Research,* 39 (Suppl. 1):S97–S113.

Loder, J. W., D. Brickman, and E.P.W. Horne, 1992. Detailed structure of currents and hydrography on the northern side of Georges Bank. *J. of Geophysical Research,* 97:331–351.

Loder, J. W., B. Petrie, and G. Gawarkiewicz, 1997. The coastal ocean off northern North America: A large-scale view. *The Sea*, in press.

Lynch, D. R., J. T. C. Ip, C. E. Naimie, and F. E.Werner, 1996. Comprehensive coastal circulation model with application to the Gulf of Maine. *Continental Shelf Research*, 16(7):875–906.

Manning, J., 1991. Middle Atlantic Bight salinity: Interannual variability. *Continental Shelf Research*, 11:123–137.

Mountain, D. G., 1991. The volume of shelf water in the Middle Atlantic Bight: seasonal and interannual variability, 1977-87. *Continental Shelf Research*, 11:251–267.

Mountain, D. G., and J. P. Manning, 1994. Seasonal and interannual variability in the properties of the surface waters of the Gulf of Maine. *Continental Shelf Research*, 14:1555–1581.

Mountain, D. G., G. Strout, and R. C. Beardsley, 1996. Surface heat flux in the Gulf of Maine. *Deep Sea Research II*, (GLOBEC Special Volume), 43:1533-1546.

Pettigrew, N. R., R. D. Hetland, and J. P. Wallinga, 1996. Cyclonic circulation of the eastern Gulf of Maine, (this volume).

Schlitz, R. J., 1997. The interaction of shelf water with warm-core rings. *J. of Geophysical Research*, submitted.

Smith, P. C., 1983. The mean and seasonal circulation off southwest Nova Scotia. *J. of Physical Oceanography*, 13:1034–1054.

Smith, P. C., 1989a. Seasonal and interannual variability off southwest Nova Scotia. *Canadian Journal of Fisheries and Aquatic Sciences*, 46(Suppl. 1):4–20.

Smith, P. C., 1989b. Circulation and dispersion on Browns Bank. *Canadian J. of Fisheries and Aquatic Sciences*, 46(4):539–559.

Smith, P. C., and F. B. Schwing, 1991. Mean circulation and variability on the eastern Canadian continental shelf. *Continental Shelf Research*, 11(8):997–1012.

Townsend, D. W., N. R. Pettigrew, P. J. Brickley, J. P. Wallinga, F. Chai, A. Thomas, C. S. Yentsch, M. E. Sieracki, C. Garside, D. Phinney, and J. Brown, 1996. Internal wave processes in the Gulf of Maine, (this volume).

Werner, S. R., 1996. The vertical structure of the bottom boundary layer southern flank of Georges Bank during late winter. MS Thesis, WHOI/MIT Joint Program in Oceanography, 93 pp. plus 48 figures.

Wiggins, J., and C. N. K. Mooers, editors, 1992. *Proceedings of the Gulf of Maine Scientific Workshop*, Urban Harbors Institute, University of Massachusetts at Boston, December, 1992.

Williams, W., 1995. The adjustment of barotropic currents at the shelfbreak to a sharp bend in the shelf topography. MS Thesis, WHOI/MIT Joint Program in Oceanography, 58 pp.

Yoshida, J., and N. S. Oakey, 1996. Characterization of vertical mixing at a tidal front on Georges Bank. *Deep Sea Research II*, (GLOBEC Special Volume) 43:1713-1744.

Zooplankton Dynamics of the Gulf of Maine and Georges Bank Region

Edward Durbin
University of Rhode Island

Abstract

Zooplankton dynamics in the Gulf of Maine and Georges Bank area are strongly influenced by the physical processes. Four major hydrographic regions can be distinguished in the Gulf of Maine and Georges Bank area, each with a distinct zooplankton community. These regions include estuarine areas where riverine input results in lower salinity, well-mixed coastal regions, the central Gulf, and shallow offshore banks such as Georges Bank. Estuarine areas are dominated by species such as *Eurytemora herdmani* and *Acartia hudsonica* which can tolerate low salinity and extreme temperature ranges. Shallow coastal regions of the Gulf (<50 m) are well-mixed and are separated from water in the central Gulf by a sharp thermal front during the summer. These regions are productive year round and support high zooplankton production by smaller copepods such as *Pseudocalanus* spp., *Paracalanus parvus, Oithona similis, Temora longicornis, Centropages typicus* and *C. hamatus*. In the central Gulf of Maine *Calanus finmarchicus* is the biomass dominant and is closely tied to the annual phytoplankon production cycle. It begins reproduction in early January in the southern Gulf of Maine and terminates in May with the demise of the spring bloom. In the northern and eastern Gulf development appears to begin later in February and March and continue through the summer. Other abundant copepods are *Metridia lucens, Pseudocalanus* spp., *Paracalanus parvus, Oithona similis, Temora longicornis, Centropages typicus* and *C. hamatus*. Georges Bank is repopulated from the Gulf of Maine by *Calanus* and *Pseudocalanus* during the winter and spring, while during the summer and fall, a resident population dominated by *Centropages hamatus* which develops from benthic resting eggs. The Maine Coastal Current and the counterclockwise gyral circulation of the central Gulf provide pathways of surface transport from the northern Gulf of Maine towards Georges Bank during the winter and spring. Repopulation of Georges Bank by *Calanus* begins during January in the region of the Northeast Peak and later on the Southern Flank as this population is advected around the Bank. On the shallow crest repopulation by *Calanus* during the winter is dependent upon episodic wind events and the timing of this is less predictable.

Introduction

The Gulf of Maine and Georges Bank are physically very dynamic regions with sharp frontal gradients, high mixing rates, and strong currents. These physical features, which show large spatial and temporal variations, strongly influence the abundance, distribution, and population dynamics of zooplankton. There are four hydrographically distinct regions in the Gulf of Maine-Georges Bank region, each having a distinct zooplankton community (Figure 1, next page). These include estuarine areas where riverine input results in lower salinity, well-mixed coastal regions, the central Gulf, and shallow offshore banks such as Georges Bank. The Bay of Fundy transitions from a region influenced by water from the central Gulf at the mouth, through well-mixed shallow regions in mid-Bay, to estuarine regions at the head of the Bay.

Estuarine Regions

These regions occur at the head of the Bay of Fundy and along the coast of the Gulf of Maine where rivers enter the Gulf. They are characterized by having lower salinity and an extreme range in temperature with a winter minimum around 0°C and a summer maximum between 18 and 20°C. The dominant copepod species in these regions are able to tolerate low salinity and include *Acartia hudsonica, A. tonsa, A. longiremis, Eurytemora herdmani*, and *Pseudodiaptomus coronatus* (Toner 1984; Townsend 1984; Lee and McAlice 1979; Daborn 1984; Turner 1994). In addition, copepods which are more coastal or shelf in origin, such as *Pseudocalanus* spp., *Paracalanus parvus, Oithona similis, Temora longicornis, Centropages typicus* and *C. hamatus,* may be abundant (Townsend 1984; Turner 1994).

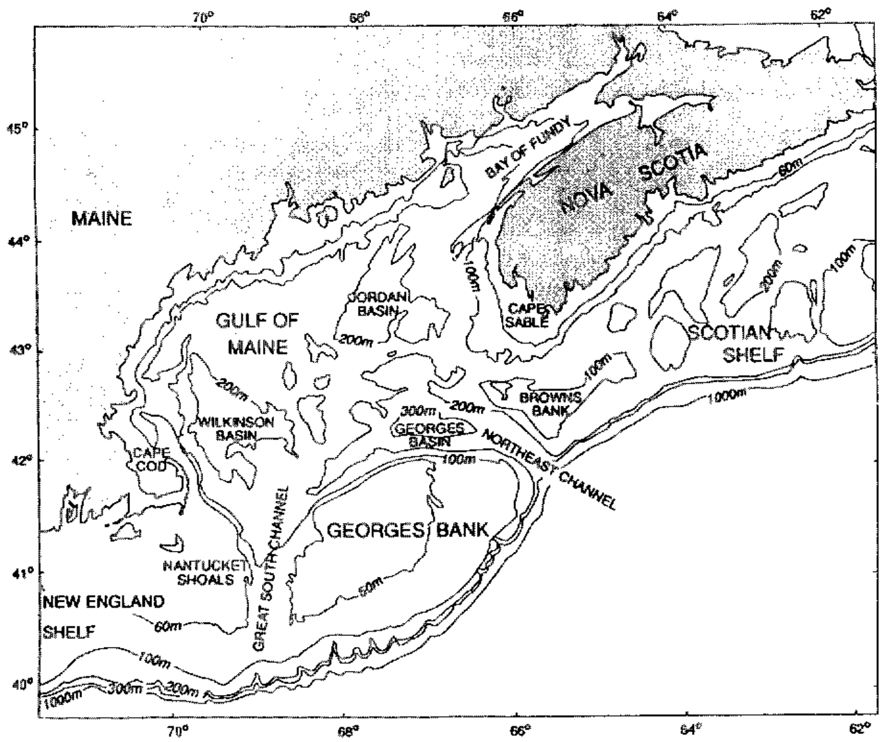


Figure 1. The topography of the Gulf of Maine.

These dominant copepod species typically show a pronounced seasonality in their abundance; a response to the extreme range in temperatures in coastal waters compared with offshore waters. In order to survive unfavorable temperatures they typically produce resting eggs. For example, *A. tonsa* and *Eurytemora herdmani* are summer dominants and survive low winter temperatures by producing resting eggs when temperatures go below about 15 °C (Zillioux and Gonzalez 1972; Sullivan and McManus 1986; Ban and Minoda 1991). In contrast, *Acartia hudsonica*, a winter dominant, will continue to grow and produce eggs at 0 °C. When temperatures begin to rise above 15 °C it begins to produce resting eggs which settle to the bottom and hatch at cold temperatures (Sullivan and McManus 1986).

There is no information about growth and reproductive rates of estuarine copepods in the Gulf of Maine region. Although estuarine regions tend to be productive, growth and reproductive rates of estuarine copepods have been reported to be seasonally food limited in nearby Narragansett Bay, Rhode Island. During the summer populations of *Acartia tonsa* were food-limited (Durbin et al. 1983), while in contrast, winter-spring populations of *A. hudsonica* show no signs of food limitation (Durbin et al. 1992). It is possible that there is a similar seasonal pattern in the degree of food limitation in Gulf of Maine estuarine waters. Detrital particles are abundant in estuarine areas and have been suggested to be an important alternate food source for *Eurytemora affinis* during the summer in Chesapeake Bay (Heinle and Flemer 1975). In the Gulf of Maine and Bay of Fundy regions the strong tidal mixing results in high levels of suspended detritus, and in the latter region may serve as an important source of food for zooplankton (Daborn 1984).

Copepod species present in estuarine regions are generally small; large copepods such as *Calanus finmarchicus* are absent. This is probably due to high predation rates by visual predators (fishes) where larger bodied forms would be selected against (Brooks and Dodson 1965). The selection for smaller bodied forms by visual predators has been well documented in freshwater systems. While there have been no estimates of predation pressure upon zooplankton in coastal Gulf of Maine waters, studies in Chesapeake Bay and Narra-

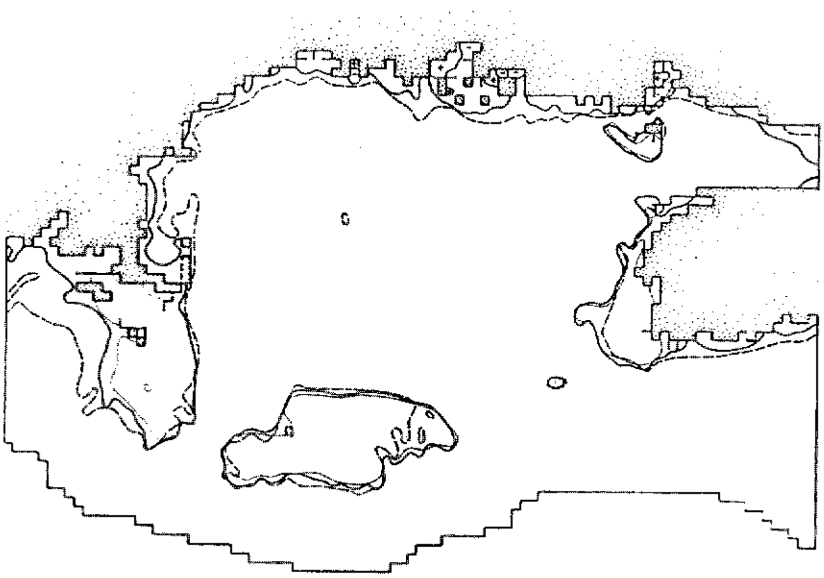


Figure 2. Predicted frontal positions for tidal and summertime wind mixing (___), using tidal dissipation rates calculated from Greenberg's (1963) model. The positions of the predicted mixing front (....) and 50 m isobath (-----) are shown. From Loder and Greenberg (1986).

gansett Bay have revealed that predation pressure by planktivorous fish (bay anchovy, menhaden) is very high (Luo and Brandt 1993; Wang and Houde 1995; Durbin and Durbin in press).

Coastal Gulf of Maine

These are shallow, well-mixed embayments and coastal regions. The zooplankton is a transition community between the truly estuarine community and the central Gulf of Maine community. Species such as *Acartia hudsonica*, *A. tonsa* and *Eurytemora herdmani* are either absent or low in abundance while *Pseudocalanus* spp., *Paracalanus parvus*, *Oithona similis*, *Temora longicornis*, *Centropages typicus* and *C. hamatus* become dominant (Toner 1984; Townsend 1984; Turner 1994). Larger central Gulf of Maine copepods such as *Calanus finmarchicus* and *Metridia lucens* tend to be low in abundance.

The 50 m isobath in the Gulf of Maine may be considered the extent of this coastal transition region (Figure 2). This region includes southwest Nova Scotia, the mid region of the Bay of Fundy, eastern Maine coastal waters, Massachusetts Bay, and a narrow band surrounding the remainder of the Gulf. These coastal well-mixed regions are most apparent during the summer when the strong tidal mixing prevents thermal stratification from developing and they can be seen as areas of colder water along the coast separated from the stratified waters of the central Gulf by a sharp thermal front (Figure 2), (Yentsch and Garfield 1981; Loder and Greenberg 1986). Because this mixing brings nutrients from deeper water to the surface (Townsend 1991), phytoplankton is higher in these regions during the summer compared with the stratified waters of the central Gulf (Yentsch and Garfield 1981; Townsend et al. 1987; Brooks and Townsend 1989; Townsend 1991). These higher phytoplankton levels in turn appear to support high zooplankton biomass and production rates (Townsend et al. 1987) although, again, we are lacking information on growth and production of zooplankton in these regions of the Gulf of Maine.

The nutrient-rich waters from these tidally-mixed regions may be entrained in the Maine Coastal Current during the summer. A plume of phytoplankton-rich, cold water has been observed which extends from the tidally well-mixed area adjacent to Grand Manan Island at the mouth of the Bay of Fundy southwest along the Maine coast (Townsend et al. 1987). Densities of copepod nauplii in this plume were lowest to the east and highest along a coastal band extending to the west of the chlorophyll maximum. Highest densities of copepodites (primarily species of *Pseudocalanus*, *Oithona*, *Acartia* and *Centropages*) occurred even further west. This was interpreted as a trophic response through an enhancement of copepod reproductive rates after they became entrained in the plume. This may be a possible cause of the higher zooplankton biomass described in the western sector of the coastal Gulf of Maine by earlier workers (Bigelow 1926; Fish and Johnson 1937; Sherman 1970).

During the winter when stratification in the central Gulf is absent, these coastal waters are not as clearly defined. However, they are distinguished from central Gulf waters by their high phytoplankton during the winter (Turner 1994). This is because the shallow depths prevent the phytoplankton from becoming light-limited (Townsend and Spinrad 1986). These high phytoplankton levels are likely to allow the dominant copepod species present (e.g., *Acartia hudsonica*, *Pseudocalanus* spp.) to continue to grow and reproduce throughout the winter (although actual reproductive rates have yet to be measured during this time).

Central Gulf of Maine

The central Gulf of Maine region is characterized by deep basins with waters isolated by Browns Bank, Georges Bank and Nantucket Shoals. Zooplankton population dynamics and distribution in this region are strongly affected by advective processes, and by the phytoplankton production cycle which in turn is controlled by the annual cycle of intense winter cooling with deep surface mixing, vernal warming, and the development of stratification. Dominant zooplankters in this region include *Calanus finmarchicus*, *Pseudocalanus* spp., *Paracalanus parvus*, *Centropages typicus*, *Centropages hamatus*, *Metridia lucens* and *Oithona similis* (Bigelow 1926; Fish and Johnson 1937 ; Sherman 1970).

There is a general counterclockwise circulation in the central Gulf with some evidence of separate gyres over the Jordan and Wilkinson Basins (Bigelow 1927; Brooks 1985; Brown and Irish 1992, 1993). Surface inflow into the Gulf occurs at SW Nova Scotia (Chapman and Beardsley 1989). This joins the Maine Coastal Current, which flows in a southwesterly direction along the northern margin of the Gulf, and which represents the northern limbs of these gyres. The Maine Coastal Current has an upstream segment extending from Grand Manan Island to Penobscot Bay where it branches with a southward-flowing arm joining the Jordan Basin gyral current (Bigelow 1927; Pettigrew 1994). The other branch continues along the coast to the Great South Channel where it bifurcates with part exiting to the south and part which either recirculates in the Great South Channel or finds its way to the northern flank of Georges Bank (Chen et al. 1995). During the spring, river runoff results in a low salinity surface plume being present in the Maine Coastal Current which has been observed as far south as the Great South Channel and extending eastwards from Cape Cod towards Georges Bank (Chen et al. 1995a). Thus there is a general transport pathway for surface waters along the coast from the northern Gulf of Maine towards the southwest, and a southeasterly flow in the central Gulf towards Georges Bank. This latter pathway is enhanced by wind during the winter and spring (Hannah et al. in press).

Surface water characteristics in the central Gulf vary widely and are controlled by seasonal surface cooling and warming, the inflow of Scotian Shelf Water and local freshwater runoff (Hopkins and Garfield 1979). In the central Gulf the phytoplankton are characterized by very low levels during winter, a spring diatom bloom which develops during the spring with the onset of thermal stratification and which terminates with the exhaustion of nutrients, and low levels again during the summer due to strong stratification (Bigelow 1926; Townsend and Spinrad 1986; Townsend et al. 1987). In the central and eastern Gulf the onset of the spring bloom, which is controlled by light limitation (Gran and Braarud 1935; Townsend and Spinrad 1986), begins in April and terminates with the exhaustion of nutrients during May (Bigelow 1926; Durbin et al. 1995a). In comparison, in the Maine Coastal Current in the southwestern region of the Gulf where the water is shallower, or where river runoff results in a reduced surface layer thickness, the spring bloom begins in March or earlier (Townsend and Spinrad 1986;Townsend et al. 1992; Durbin et al. 1995a) and terminates during late April (Durbin et al. 1995a). The demise of the spring bloom in this region is enhanced by strong stratification caused by lower salinity surface water from spring river runoff which is carried into this region by the Maine Coastal Current (Durbin et al. 1995a).

The very strong pycnocline which develops during the summer results in the isolation of the surface layer from nutrient-rich waters below and severe nutrient limitation in the shallow surface layer. Typically a subsurface chlorophyll maximum is present (Holligan et al. 1984; Townsend et al. 1984; Durbin et al. 1995a) with production being limited by the rates of diffusion of nutrients through this thermocline and the level of nutrient recycling by heterotrophs. While there is some suggestion that there is enhanced zooplankton biomass in or above this subsurface chlorophyll maximum (Townsend et al. 1984), most of the phytoplankton in this layer is less than 5 μm (Durbin et al. 1995a) and too small to be eaten by the dominant copepods such as *Calanus* (Frost 1972).

The large copepod *Calanus finmarchicus* is the dominant copepod in the Gulf of Maine in terms of bio-

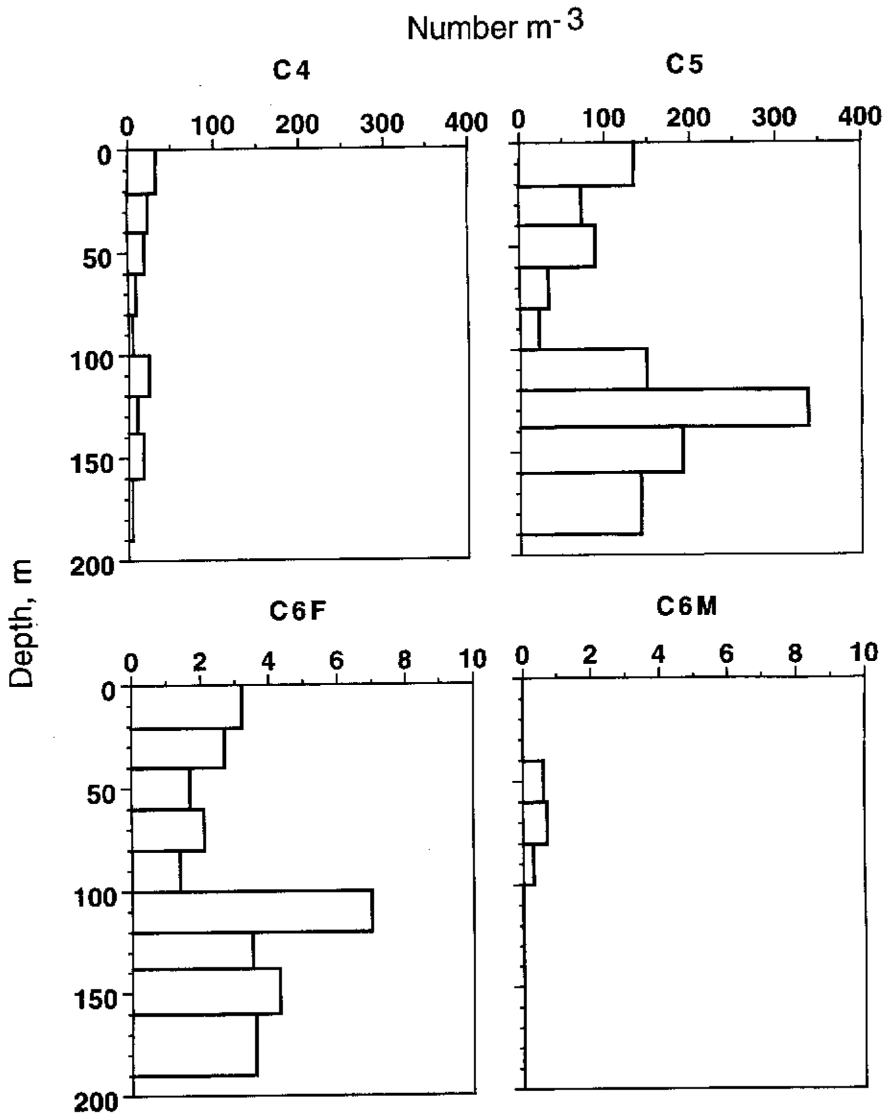


Figure 3. Night-time depth distribution of *Calanus finmarchicus* older copepodites in the southern Gulf of Maine during November 10, 1994. From Durbin et al. 1997.

mass (Bigelow 1926; Fish and Johnson 1937; Sherman 1970; Sherman et al. 1983), although smaller species, particularly *Oithona* spp., are numerically dominant (Durbin et al. in preparation). The population dynamics of *C. finmarchicus* are keyed to the annual phytoplankton production cycle described above. *C. finmarchicus* spends late summer and fall at depth in a resting or quiescent state usually as the fifth copepodite stage (C5). It is not clear whether this represents a true diapause (Miller et al. 1991). Molting to the adult stage takes place during winter and spawning begins when sufficient food levels are reached (Conover 1988). It then passes through one or more generations before descending again to rest through the summer and fall.

The U.S. GLOBEC Georges Bank Program study has provided much more detail on the life cycle of *Calanus finmarchicus* in both the Gulf of Maine and on Georges Bank through the collection of depth stratified samples which include all of the life stages (Durbin et al. 1997). While these observations support the general pattern described above, there are some important differences. For example, in the southwestern Gulf of Maine during November most of the *Calanus* population was present as C5 as expected, but rather than resting near the bottom, about one third were in the upper 80 m (Figure 3) and actively feeding (Durbin et al. 1997). By January adult females formed a large proportion of the older stage *Calanus* population in this region. These females were actively feeding and reproducing and a large cohort of young nauplii were present (Figure 4). Based on these demographic observations and estimates of the development rate of early *Calanus* life stages, it was concluded that emergence from the resting phase and spawning must have commenced in early and late December respectively (Durbin et al. 1997). This arousal and onset of spawning is much earlier than previously considered.

In contrast, during 1995 the arousal of *Calanus* took place a little later in Georges Basin in the eastern

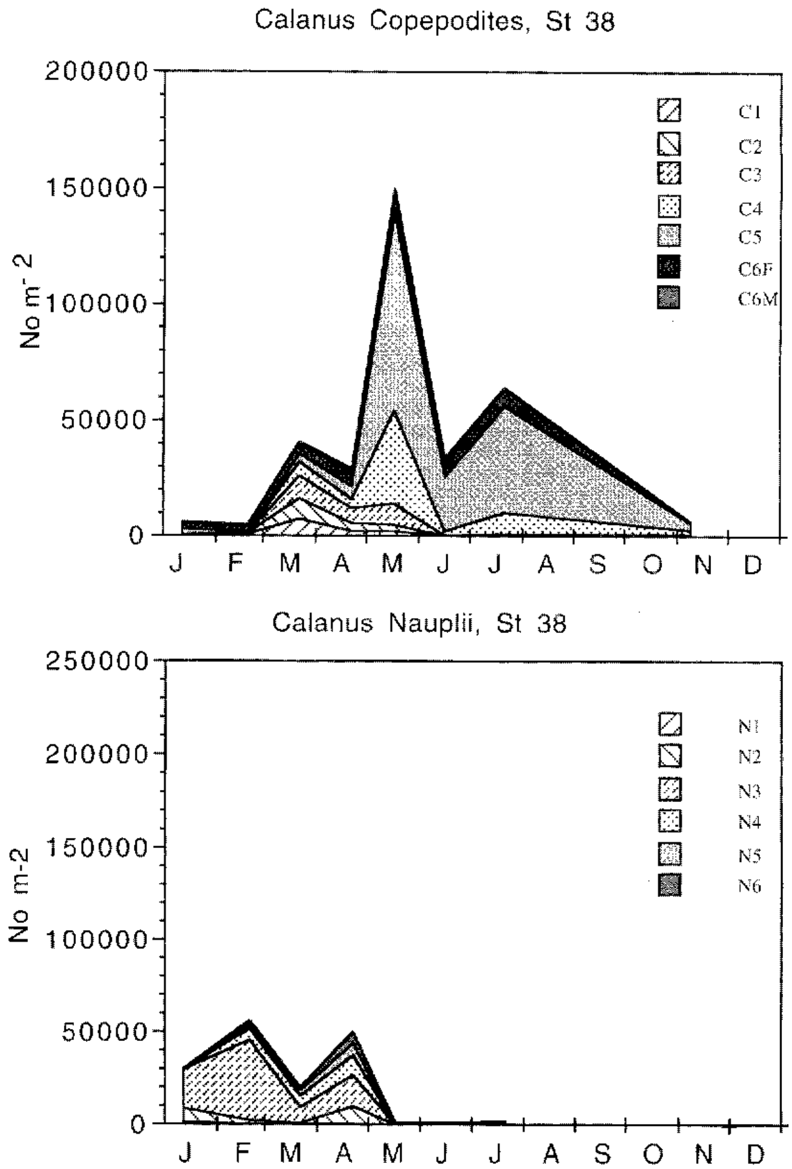


Figure 4. Abundance of *Calanus finmarchicus* nauplii (lower) and copepodites (upper) at U.S. GLOBEC Georges Bank Program survey St. 38 in the southern Gulf of Maine during 1995. From Durbin et al. (in preparation).

Gulf of Maine. *Calanus* C5 copepodites were still dominant during January (73.4% of total copepodites) and most of these were present at depths >100 m. Young nauplii were present, but in much lower abundance compared with the Great South Channel, and did not begin to increase until February (Figure 5). In the northern Gulf and in the Bay of Fundy spawning of *Calanus* appears to begin even later during March (Fish 1936). This suggests that there are spatial differences in timing of arousal of *Calanus* in the Gulf of Maine. However, there is a need for further information during the winter to document these spatial differences in timing of arousal and onset of spawning. At present we do not know what the arousal mechanism for *C. finmarchicus* is, a critical gap in our knowledge.

During the winter and spring nauplii were continuously present in the southern Gulf of Maine indicating a long spawning period (Figure 4). This may be due to prolonged spawning by the same initial females (Plourde and Runge, 1993, found that *Calanus* continued to spawn for more than 60 days), or a delay in arousal and initiation of spawning of some individuals. Since both Georges Basin and the Great South Channel are at the downstream end of the current pathways from the northern Gulf of Maine where arousal appears to begin later, there could also be a continual input of younger adult females from this latter region leading to this prolonged spawning.

The winter generation of *Calanus* reached maturity during May and June in the Great South Channel and in Georges Basin (Figures 4, 5) and some of the C5 copepodites had begun their ontogenetic migration to the bottom to enter the resting phase. In the Great South Channel region nauplii had disappeared by May (Figure 4). This was due to an absence of egg production by *Calanus* in this region during May of 1995 (Runge and Plourde personal communication), probably because of extreme food limitation. The strong stratification of the water column, low nutrients and phytoplankton abundance and low *in situ* feeding rates in this region during 1988 and

1989 (Durbin et al. 1995 a, b) support this suggestion of food limitation. In Georges Basin, in contrast, there was a very large cohort of *Calanus* nauplii produced during June (Figure 5). However, these did not appear as copepodites in July suggesting high mortality or advection of the population out of the area.

In the northern Gulf of Maine and the Bay of Fundy region spawning by *Calanus* not only commences later during the spring as noted above, but also continues later during the summer. Fish (1936) found significant numbers of eggs and young nauplii in these regions during August and September. The later spawning to the north and east complicates our picture of *Calanus* dynamics in the Gulf of Maine because the general surface flow patterns are from these regions towards the south and west. In the northern Great South Channel region of the southwestern Gulf of Maine, younger developmental stages of *C. finmarchicus*, and smaller individuals within a stage, were found by Durbin et al. (1995c) in the upstream region of the sampling area, apparently being carried into the region by the Maine Coastal Current.

While *Calanus finmarchicus* is abundant throughout the Gulf of Maine (Bigelow 1926; Meise and O'Reilly 1996), there are regions where older stages of *Calanus* form dense patches which are active feeding sites for right whales. These occur in Cape Cod Bay during late winter and early spring (Mayo and Marx 1990; Payne et al. 1990), the northern Great South Channel region during late spring and early summer (Scott et al. 1985; Wishner et al. 1988; Wishner et al. 1995), and at the mouth of the Bay of Fundy near Grand Manan Island during late summer (Brown and Gaskin 1989; Murison and Gaskin 1989; Woodley and Gaskin 1996). In the Great South Channel region *Calanus* appears to be carried into the region by a southward-flowing low salinity plume of the Maine Coastal Current (Durbin et al. 1995c; Wishner et al. 1995). During June of 1989 most of the *Calanus* in this region was present in a surface layer and did not undergo diel vertical migration (Durbin et al. 1995c). The highest copepod concentrations were located in regions of convergence where the plume turns eastward away from Cape Cod and towards Georges Bank (Wishner et al.

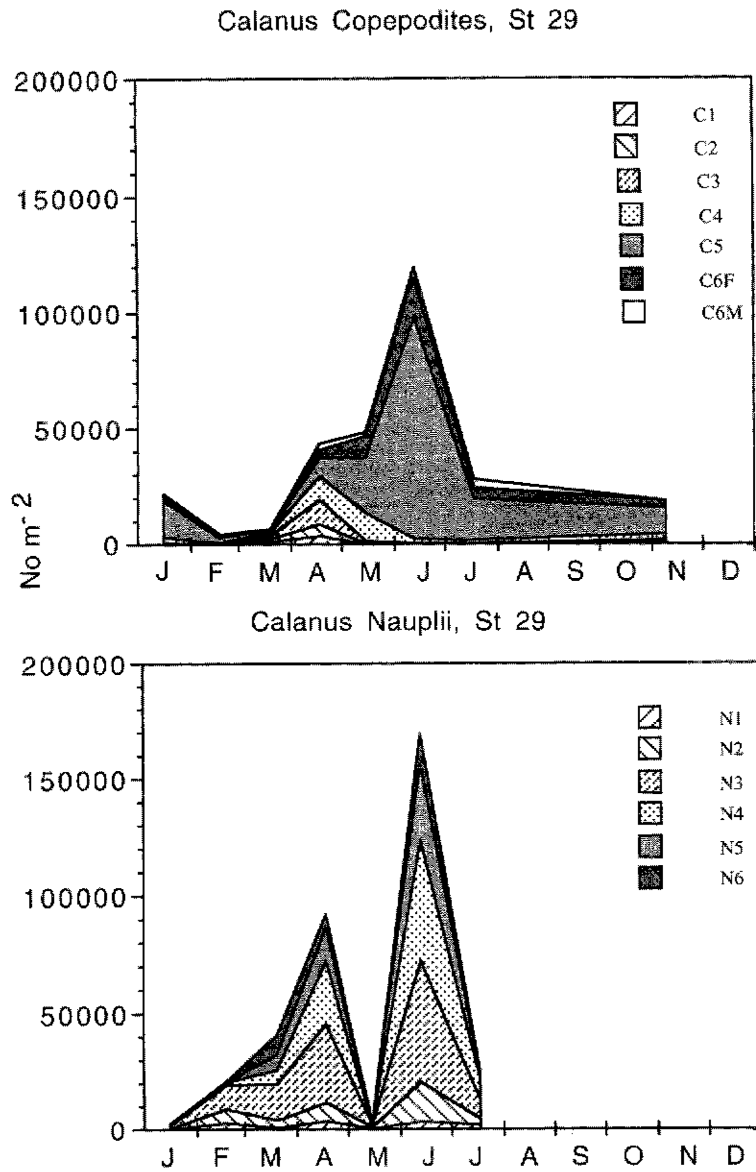


Figure 5. Abundance of *Calanus finmarchicus* nauplii (lower) and copepodites (upper) at U.S. GLOBEC Georges Bank Program survey St. 29 in the Georges Basin of the Gulf of Maine during 1995. From Durbin et al. (in preparation).

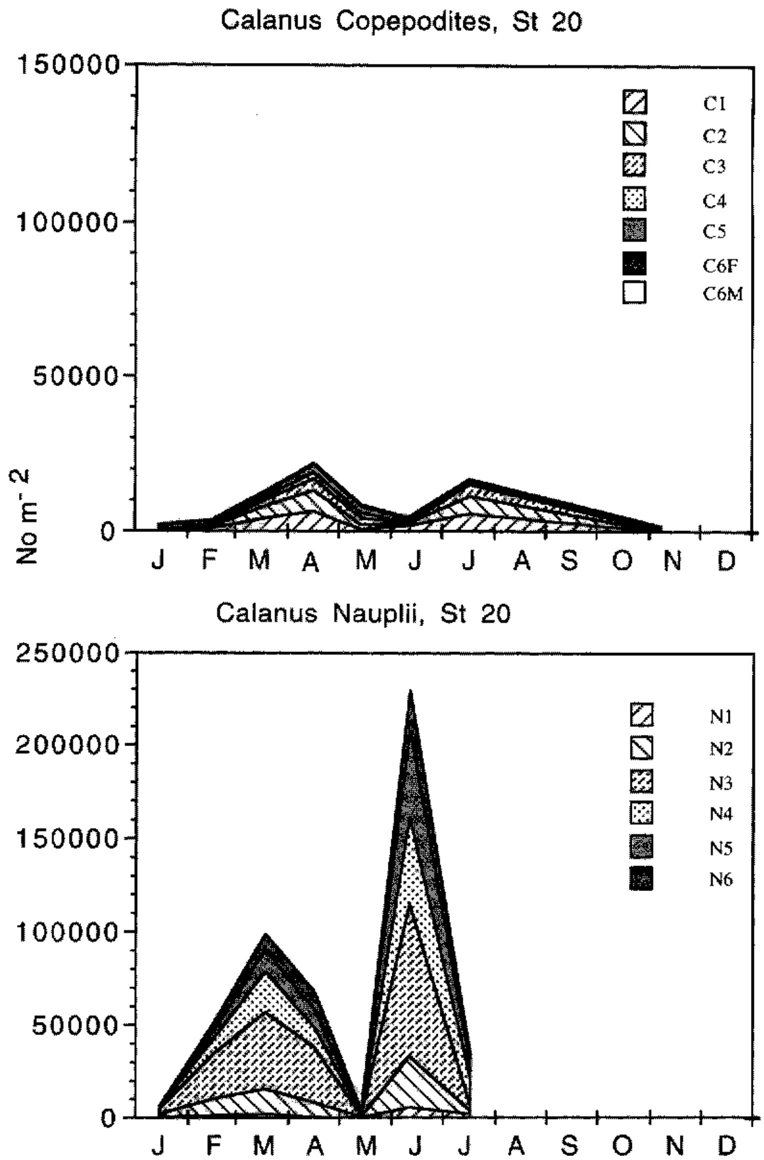


Figure 6. Abundance of *Calanus finmarchicus* nauplii (lower) and copepodites (upper) at U.S. GLOBEC Georges Bank Program survey St. 20 in the Georges Basin of the Gulf of Maine during 1995. From Durbin et al. (in preparation).

1995; Chen et al. 1995). Peak copepod abundances (30,800 m^{-3}) seemed to be associated with the leading edge of the low salinity water. At times during 1989 there was a visibly red surface layer and a bucket sample from one of these had a concentration of 331,000 m^{-3} (Wishner et al. 1995). The mechanisms of concentration were not resolved but probably include small-scale vertical movements of *Calanus* in regions of convergence. The occurrence of *Calanus* in these dense surface layers is highly seasonal; during 1988 sampling took place several weeks earlier than in 1989 and no dense surface patches were observed. The spring bloom was still continuing in parts of the region during late June-early May of 1988 but had ended by late May-early June, 1989 (Durbin et al. 1995c). In some parts of the Great South Channel region during 1988 *Calanus* was undergoing strong diel vertical migration but not in others, while during 1989 there was no migration (Durbin et al. 1995c). A more complete understanding of the seasonal changes in vertical migration behavior by *Calanus* in the Gulf of Maine and processes controlling it is important in considering its transport by currents.

Georges Bank

The dominant zooplankton species are similar to those described above for the Gulf of Maine and include *Calanus finmarchicus* and *Pseudocalanus* spp., which are winter/spring dominants, *Paracalanus parvus*, *Centropages typicus* and *C. hamatus* which are dominant in summer and fall, and *Metridia lucens* and *Oithona similis* which are always abundant (Sherman et al. 1983; Davis 1987; Kane 1993). *Calanus finmarchicus* is by far the most dominant copepod in terms of biomass (Davis 1987) and is the focus of the discussion below.

Calanus is present in very low numbers on Georges Bank during the fall and repopulation takes place from the resting populations present in the deeper waters of the Gulf of Maine (Davis 1987; Meise and O'Reilly 1996; Durbin et al. in press). This repopulation began during 1995 in early January in the region of the

Northeast Peak of Georges Bank with an increase in abundance of adult females and the appearance of a cohort of young nauplii (Durbin et al. in press; Figure 6). Elsewhere on the Bank at this time *Calanus* was almost entirely absent. At the western end of the Southern Flank, which is downstream from the Northeast Peak, *Calanus* numbers lagged behind those at the Northeast Peak and did not begin to increase until March (Figure 7). This population of *Calanus* on the Flank matured during April and May with an increase in the proportion of C5 and adult females (Durbin et al. in prep; Figure 6, 7). The abundance of nauplii was at a minimum during May but increased again during June marking the appearance of a large second generation. This generation quickly matured with warmer summer temperatures and by July was dominated by older stage copepodites. It is not known if are any further large reproductive events by *Calanus* on the Bank. By the following November *Calanus* was present in very low numbers (Figures 6, 7). These data demonstrate quite clearly that there was one prolonged first generation of *Calanus* which matured during May, followed by a second, more brief one in June.

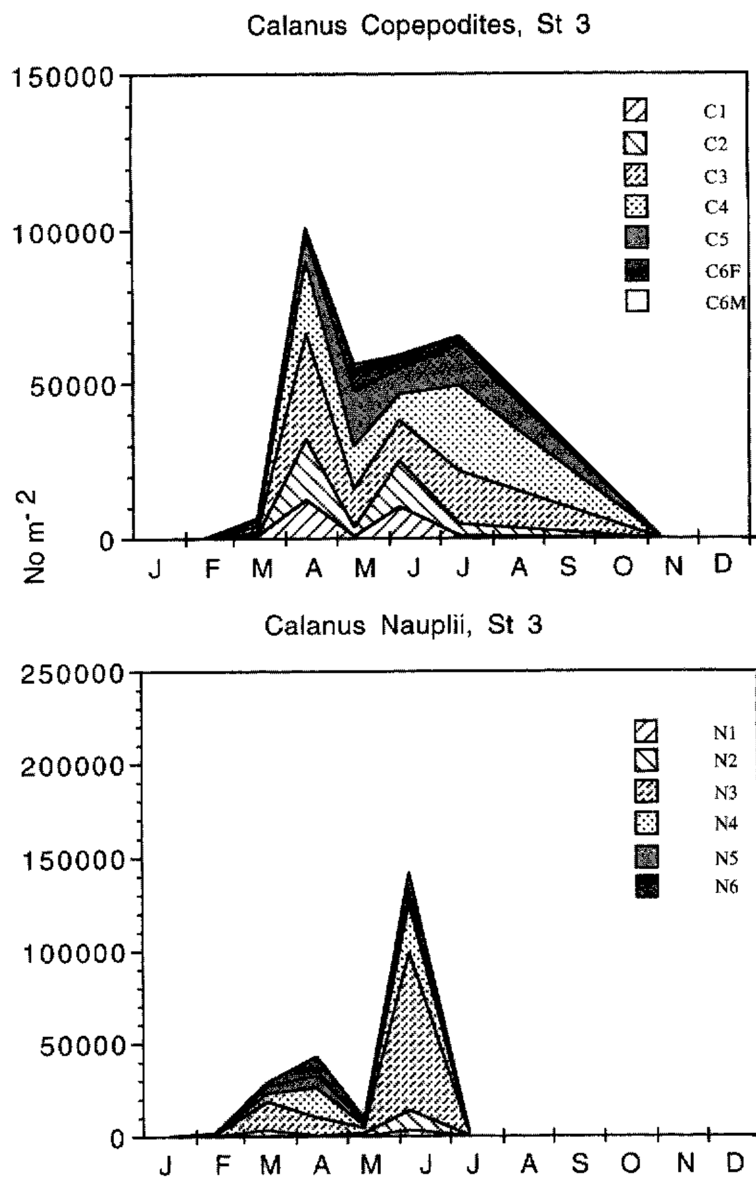


Figure 7. Abundance of *Calanus finmarchicus* nauplii (lower) and copepodites (upper) at U.S. GLOBEC Georges Bank Program survey St. 3 in the Georges Basin of the Gulf of Maine during 1995. From Durbin et al. (in preparation).

In contrast to the early repopulation of the Northeast Peak by *Calanus* repopulation of the shallow central region of the Bank was delayed with almost no animals appearing until March, when a relatively mature population which included both nauplii and copepodites appeared (Durbin et al. in prep; Figure 8, next page). This population matured during April, with the appearance of relatively large numbers of adult females. However, despite the presence of these females, nauplii declined during April and by May *Calanus* had essentially disappeared from the Crest. A similar temporal pattern was observed by Meise and O'Reilly (1996).

Advection appears to play a major role in controlling *Calanus* population dynamics on the Bank, particularly during the winter when *Calanus* repopulates the Bank. Different types of advective processes appear to be dominant on the Crest and the Flank. On the Northeast Peak and the Southern Flank the zooplankton is dominated by the general gyral circulation in the region

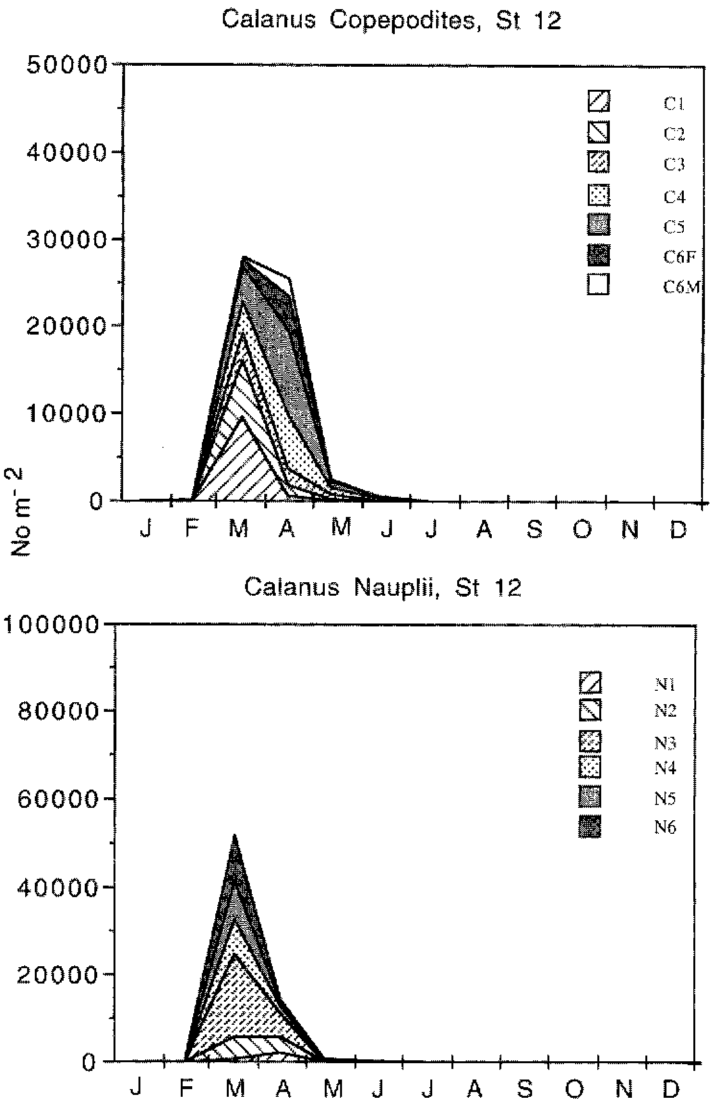


Figure 8. Abundance of *Calanus finmarchicus* nauplii (lower) and copepodites (upper) at U.S. GLOBEC Georges Bank Program survey St. 12 in the Georges Basin of the Gulf of Maine during 1995. From Durbin et al. (in preparation).

resulting from tidal rectification. This produces a strong jet along the northern flank which flows onto the Northeast Peak, and subsequently drifts westward along the Southern Flank (Butman and Beardsley 1987; Butman et al. 1987). *Calanus* appears first during winter on the Northeast Peak and then is transported westward by this current appearing later on the western end of the Southern Flank. On the Northeast Peak, where *Calanus* is first advected onto the Bank from the Gulf of Maine, nauplii constitute the greatest proportion of the population. As this population is advected along the Southern Flank it matures as seen by the greater proportion of copepodites at the western end of the Southern Flank. These patterns indicate that there is a predictable and continuous input of *Calanus* nauplii on the Northeast Peak during February and March. Cod and haddock, whose eggs hatch during winter and early spring (Smith 1983), have their primary spawning region on Georges Bank on the Northeast Peak. This suggests that they have responded on an evolutionary time scale by adopting the naupliar focal point for recurrent spawning.

The clockwise circulation of a maturing population of copepods around Georges Bank has been modeled by Davis (1984) for *Pseudocalanus* sp. He noted that the population age structure of *Pseudocalanus* sp. on Georges Bank during February 1975 had distinct shifts from younger to older developmental stages in a clockwise pattern around the Bank, and hypothesized that this spatial pattern resulted from the interaction of copepod population dynamics and the mean circulation of seawater around the Bank beginning with the advection of animals from the southern Gulf of Maine onto the Northeast Peak. A combined physical/biological model was developed which simulated this pattern. Recent U.S. GLOBEC Georges Bank studies have shown a pattern of abundance of *Pseudocalanus* which was similar to that described above for *Calanus* during the winter-spring period and it would appear that this is a realistic model for both populations.

On the Crest of Georges Bank in contrast, the temporal changes in *Calanus* abundance were quite different and appear to be controlled by episodic wind events during the winter which result in slab flow of surface waters off the Crest of the Bank and replacement with water from the Gulf of Maine. During 1995 the abundance and stage distribution data for *Calanus* suggest that there was little advection of water from the Gulf of

Maine onto the Crest until late February/early March when the relatively mature population of *Calanus* appeared (Figure 8). After this time there again appeared to be little further exchange of Crest water with either the Gulf of Maine and the deeper waters on the Northeast Peak and the Southern Flank. ARGOS drifters deployed in the region of the Crest at monthly intervals during the winter and spring of 1995 support this suggestion that the Crest is quite isolated, showing unorganized, non-dispersive patterns during the winter and early spring, and then an organized recirculation pattern spinning up in May (Beardsley and Limeburner personal communication). Wind events dominate during the winter-early spring phase and a wind event during the middle of February resulted in the movement of surface waters off the Crest towards the south and a replacement from the Gulf of Maine with *Calanus* containing water. Because of this dependence on episodic wind events, the timing of the repopulation of the Crest may show considerable interannual variation.

The data for 1995 described above indicates that *Calanus* repopulates Georges Bank from the Gulf of Maine. The supply of *Calanus* from the Gulf of Maine to Georges Bank has been explored by Hannah et al. (in press) by numerically tracking particles in realistic 3-D seasonal-mean and tidal flow fields. They found that the winter-spring surface layer in the Gulf of Maine, with generally southward drift, can act as a conveyor belt for the transport of animals to Georges Bank. However, repopulation of the crest and the Northeast Peak were predicted to proceed at the same rate, a result different from that observed during 1995. This difference is probably due to the fact that modeled results were based on mean wind fields and do not include the episodic nature of actual storm events.

Another pathway for the advection of *Calanus* onto Georges Bank is via Scotian Shelf water which may regularly cross the Northeast Channel during winter and early spring and become entrained in the circulation along the Southern Flank (Mountain 1991). Satellite imagery suggests a regular occurrence of this process (Bisagni et al. 1996) and it may provide another mechanism for input of *Calanus* to Georges Bank. Estimation of the volume of water involved and the concentration of copepods within it, should provide an indication of the relative significance of this process compared with the pathways described above.

Once *Calanus* reaches the Bank *in situ* abundance is controlled by processes of birth, growth, and mortality, as well as advective losses off the Bank. Although food is generally considered to be non-limiting for copepod reproduction and growth on the Bank, little is actually known about these rates. These processes are the focus of ongoing U.S. GLOBEC Georges Bank studies, and preliminary data provide evidence both for and against the presence of food limitation. Egg production rates by *Calanus* were generally near maximal on the Bank throughout the winter-spring period and rates only appeared to be food-limited in the northern Great South Channel region of the Gulf of Maine during June (Runge and Plourde personal communication). This would indicate that population recruitment rates are largely controlled by adult female abundance. There was no evidence for a hiatus in reproductive rates during May which would have led to the low abundance of nauplii observed at this time, or of an increase during June with the production of the second generation. In contrast, *in situ* growth experiments carried out during 1995 support the presence of food limitation at this time, particularly on the Crest where growth rates were significantly lower than on the Northeast Peak or Southern Flank, and lower than maximal laboratory growth rates (Campbell and Durbin in preparation). The second generation of *Calanus* observed during June may be related to increased egg production rates associated with the development of stratification and the presence of a chlorophyll maximum at the pycnocline. During June of 1994 very low numbers of *Calanus* nauplii were present at a non-stratified station on the Northeast Peak, while on the Southern Flank stratification had set in and there was a well developed chlorophyll maximum and a large cohort of young nauplii (Durbin in preparation).

At present there are no direct estimates of mortality of *Calanus* on the Bank but it is undoubtedly very high, particularly on the Crest. Invertebtrate predators such as chaetognaths (Lough and Trites 1989; Sullivan and Meise 1996) and the hydroid *Clytia*, a voracious copepod feeder (Madin et al. 1996), are most abundant on the Crest reaching highest concentrations during May (Durbin unpublished). High predation rates may be responsible for the disappearance of *Calanus* from the Crest during April and May.

Advective losses are likely to be also important in controlling *Calanus* abundance on the Bank. These losses can be through wind events which transport water and animals off the Bank (Walford 1938; Cohen et al. 1986), transport of water from the western end of the Bank to the Mid-Atlantic Bight (Polacheck et al. 1992), and impingement of warm core rings onto the Southern Flank which entrain and transport organisms off the Bank (Morgan and Bishop 1977; Smith 1978; Bisagni 1983; Joyce et al. 1992). This latter process also results in the appearance of expatriate slope species onto the S. Flank.

Interannual Variability in Zooplankton Abundance

Abundance of the dominant copepods on Georges Bank shows considerable interannual variability. Mean abundance of adults and late stage copepodites of *Calanus finmarchicus* during late spring varied between 894 m^{-3} and 46 m^{-3} between 1977 and 1986, while mean annual abundance of *Calanus* on Georges Bank showed about a five-fold variation between 1977 and 1985 (Kane 1993). Other copepods such as *Pseudocalanus* spp., *Centropages typicus*, *C. hamatus* and *Metridia lucens* showed a similar range of variability (Kane 1993). In the case of *Pseudocalanus* the interannual abundance trend was very similar to that of *Calanus*. In the Gulf of Maine, Jossi and Goulet (1993) found that *Calanus finmarchicus* collected from continuous plankton recorders showed an increasing trend in abundance between 1961 and 1989, while other copepods showed no consistent long term trend in abundance. However, all copepods but *Metridia lucens* covaried.

In the Great South Channel region of the southern Gulf of Maine, *Calanus finmarchicus* was the overwhelming dominant during late spring in 1986, 1988 and 1989 forming dense almost monospecific patches (Wishner et al. 1988; Wishner et al. 1995). However, during late spring in 1991 *Calanus* was relatively low in abundance and *Metridia lucens* (a large copepod but which does not have a large oil sac) was a co-dominant (Durbin and Green unpublished). During that year the right whales left the region early, while during the subsequent year they were absent (Kenney personal communication). At present, reasons for such interannual variability are not well understood.

Acknowledgments

This contribution has been sponsored by the U.S. GLOBEC Georges Bank Program with support coming from NSF Grant No. OCE9313677 and NOAA Grant No. NA47FE0457.

References

Ban, S. and T. Minoda. 1991. The effect of temperature on the development and hatching of diapause and subitaneous eggs in *Eurytemora affinis* (Copepoda: Calanoida) in Lake Ohnuma, Hokkaido, Japan. *Bull. Plankton Soc. Japan,* Spec. Vol.:299-308.

Bigelow, H. B. 1926. Plankton of the offshore waters of the Gulf of Maine. *Bull. Bureau Fisheries, U.S.* 40:1-509.

Bigelow, H. B. 1927. Physical oceanography of the Gulf of Maine. *Bull. Bureau Fisheries, U.S.* 40:511-1027.

Bisagni, J. J. 1983. Lagrangian current measurements within the eastern margin of a warm-core Gulf Stream ring. *J. Phys. Oceanogr.* 13:709-715.

Bisagni, J. J., R. C. Beardsley, C. M. Ruhsam, J. P. Manning, and W. Williams. 1996. Historical and recent evidence concerning the presence of Scotian shelf water on southern Georges Bank. *Deep-Sea Res.* 43:1439-1471.

Brooks, D. A. 1985. The vernal circulation in the Gulf of Maine. *J. Geophys. Resch.* 90:4687-4705.

Brooks, J. L. and S. I. Dodson. 1965. Predation, body size, and composition of plankton. *Science* 150:28-35.

Brooks, D. A. and D. W. Townsend. 1989. Variability of the coastal current and nutrient pathways in the eastern Gulf of Maine. *J. Mar. Res.* 47:303-321.

Brown, R. G. B. and D. E. Gaskin. 1989. Summer zooplankton distributions at the surface of the outer Bay of Fundy, eastern Canada. *Can. J. Zool.* 67:2725-2730.

Brown, W. S. and J. D. Irish. 1992. The annual evolution of geostrophic flow in the Gulf of Maine: 1986-1987. *J. Phys. Oceanogr.* 22:445-473.

Brown, W. S. and J. D. Irish. 1993. The annual variation of water mass structure in the Gulf of Maine: 1986-1987. *J. Mar. Res.* 51:53-107.

Butman, B. and R. C. Beardsley. 1987. Physical oceanography. In *Georges Bank*, ed. R. H. Backus, 88-98. Cambridge: MIT Press.

Butman, B., J. W. Loder, and R. C. Beardsley. 1987. The seasonal mean circulation: observation and theory. In *Georges Bank*, ed. R. H. Backus, 125-138. Cambridge: MIT Press.

Chapman, D. C. and R. C. Beardsley. 1989. On the origin of shelf water in the Middle Atlantic Bight. *J. Phys. Oceanogr.* 19:384-391.

Chen, C. S., R. C. Beardsley, and R. Limeburner. 1995. Variability of currents in late spring in the northern Great South Channel. *Cont. Shelf Res.* 15(4-5):451-473.

Cohen, E. B., D. G. Mountain, and R. G. Lough. 1986. Possible factors responsible for the variable recruitment of the 1981, 1982, and 1983 year-classes of haddock (*Melanogrammus aeglefinus* L.) on Georges Bank. *Northw. Atl. Fish. Org. SCR Doc. 86/100,* Ser. No. N1237. 27 pp.

Conover, R. J. 1988. Comparative life histories in the genera *Calanus* and *Neocalanus* in high latitudes of the northern hemisphere. *Hydrobiologia* 167/168:127-142.

Daborn, G. R. 1984. Zooplankton studies in the upper Bay of Fundy since 1976. *Can. Tech. Rep. Fish. Aquat. Sci.* no. 1256:135-162.

Davis, C. S. 1984. Interaction of a copepod population with the mean circulation on Georges Bank. *J. Mar. Res.* 42:573-590.

Davis, C. S. 1987. Zooplankton life cycles. In *Georges Bank,* ed. R. H. Backus, 256-267. Cambridge: MIT Press.

Durbin, A. G. and E. G. Durbin. (In press). The role of menhaden predation on plankton populations in Narragansett Bay, RI. *Estuaries.*

Durbin, E. G., A. G. Durbin, T. J. Smayda, and P. G. Verity. 1983. Food limitation of production by adult *Acartia tonsa* in Narragansett Bay, Rhode Island. *Limnol. Oceanogr.* 28(6):1199-1213.

Durbin, E. G., A. G. Durbin, and R. G. Campbell. 1992. Body size and egg production in the marine copepod *Acartia hudsonica* during a winter-spring diatom bloom in Narragansett Bay. *Limnol. Oceanogr.* 37(2):342-360.

Durbin, E. G., A. G. Durbin, and R. C. Beardsley. 1995a. Springtime nutrient and chlorophyll *a* concentrations in the southwestern Gulf of Maine. *Cont. Shelf Res.* 15(4-5):433-450.

Durbin, E. G., R. G. Campbell, S. L. Gilman, and A. G. Durbin. 1995b. Diel feeding behaviour and ingestion rate in the copepod *Calanus finmarchicus* in the southern Gulf of Maine during late spring. *Cont. Shelf Res.* 15(4-5):539-570.

Durbin, E. G., S. L. Gilman, R. G. Campbell, and A. G. Durbin. 1995c. Abundance, biomass, vertical migration and estimated development rate of the copepod *Calanus finmarchicus* in the southern Gulf of Maine during late spring. *Cont. Shelf Res.* 15(4-5):571-591.

Durbin, E. G., J. A. Runge, R. G. Campbell, P. R. Garrahan, M. C. Casas and S. Plourde. 1997. Late fall-early winter recruitment of *Calanus finmarchicus* on Georges Bank. *Mar. Ecol. Prog. Ser.* 151:103-114.

Fish, C. J. 1936. The biology of *Calanus finmarchicus* in the Gulf of Maine and Bay of Fundy. *Biol. Bull.* 70: 118-141.

Fish, C. J. and M. W. Johnson. 1937. The biology of the zooplankton population in the Bay of Fundy and Gulf of Maine with special reference to production and distribution. *J. Biol. Bd. Can.* 3:189-322.

Frost, B. W. 1972. Effects of size and concentration of food particles on the feeding behavior of the marine planktonic copepod *Calanus pacificus. Limnol. Oceanogr.* 17(6):805-815.

Gran, H. H. and T. Braarud. 1935. A quantitative study of the phytoplankton in the bay of Fundy and the Gulf of Maine (including observations on hydrography, chemistry and turbidity). *J. Biol. Board Can.* 1:279-467.

Hannah, C. G., C. E. Naimie, J. W. Loder, and F. E. Werner. (In press). Upper-ocean transport mechanisms from the Gulf of Maine to Georges Bank, with implications for *Calanus* supply. *Cont. Shelf. Res.*

Heinle, D. R. and D. A. Flemer. 1975. Carbon requirements of a population of the estuarine copepod *Eurytemora affinis. Mar. Biol.* 31:235-247.

Holligan, P. M., P. H. leB. Williams, D. Purdie, and R. P. Harris. 1984. Photosynthesis, respiration, and N supply of plankton populations in stratified, frontal and tidally mixed shelf waters. *Nature* 17:201-213.

Hopkins, T. S. and N. Garfield III. 1979. Gulf of Maine intermediate water. *J. Mar. Res.* 37:103-139.

International Council for the Exploration of the Sea. 1985. *Biological and physical oceanographic correlatives to cetacean density distribution in the Great South Channel..* Prepared by G. P. Scott, R. D. Kenney, R. E. Owen, M. A. M. Hyman, and H. E. Winn. Copenhagen. Document C.M. 1985/N:6/REF:L. 36 pp.

Jossi, J. W. and J. R. Goulet Jr. 1993. Zooplankton trends: US north-west shelf ecosystem and adjacent regions differ from north-east Atlantic and North Sea. *ICES J. Mar. Sci.* 50:303-313.

Joyce, T. M., J. K. B. Bishop, and O. B. Brown. 1992. Observations of offshore shelf-water transport induced by a warm-core ring. *Deep-Sea Res.* 39:S97-S113.

Kane, J. 1993. Variability of zooplankton biomass and dominant species abundance on Georges Bank, 1977-1986. *Fish. Bull.* 91(3):464-474.

Lee, W. Y. and B. J. McAlice. 1979. Seasonal succession and breeding cycles of three species of *Acartia* (Copepoda: Calanoida) in a Maine estuary. *Estuaries* 2:228-235.

Loder, J. W. and D. A. Greenberg. 1986. Predicted positions of tidal fronts in the Gulf of Maine. *Cont. Shelf Res.* 6:397-414.

Lough, R. G. and R. W. Trites. 1989. Chaetognaths and oceanography on Georges Bank. *J. Mar. Res.* 47:343-369.

Luo, J. and S. B. Brandt. 1993. Bay anchovy *Anchoa mitchilli* production and consumption in mid-Chesapeake Bay based on a bioenergetics model and acoustic measures of fish abundance. *Mar. Ecol. Prog. Ser.* 98(3):223-236.

Madin, L. P., S. M. Bollens, E. Horgan, M. Butler, J. Runge, B. K. Sullivan, G. Klein-MacPhee, E. Durbin, A. G. Durbin, A. Bucklin, and M. E. Clarke. 1996. Voracious planktonic hydroids: unexpected predatory impact on a coastal marine ecosystem. *Deep-Sea Res.* 43: 1823-1829.

Mayo, C. A. and M. K. Marx. 1990. Surface foraging behaviour of the North Atlantic right whale, *Eubalaena glacialis*, and associated zooplankton characteristics. *Can. J. Zool.* 68:2214-2220.

Meise, C. and J. E. O'Reilly. 1996. Spatial and seasonal patterns in abundance and age-composition of *Calanus finmarchicus* in the Gulf of Maine and on Georges Bank: 1977-1987. *Deep-Sea Res.* 43:1503-1519.

Miller, C. B., T. J. Cowles, P. H. Wiebe, N. J. Copley, and H. Grigg. 1991 Phenology in *Calanus finmarchicus*; hypotheses about control mechanisms. *Mar. Ecol. Prog. Ser.* 72:79-91.

Morgan, C. W. and J. M. Bishop. 1977. An example of Gulf Stream eddy-induced water exchange in the mid-Atlantic bight. *J. Phys. Oceanogr.* 7:472-479.

Mountain, D. G. 1991 The volume of shelf water in the Middle Atlantic Bight: seasonal and interannual variability, 1977-1987. *Cont. Shelf Res.* 11:251-267.

Murison, L. D. and D. E. Gaskin. 1989. The distribution of right whales and zooplankton in the Bay of Fundy, Canada. *Can. J. Zool.* 67:1411-1420.

Payne, P. M., D. N. Wiley, S. B. Young, S. Pittman, P. J. Clapham, and J. W. Jossi. 1990. Recent fluctuations in the abundance of baleen whales in the southern Gulf of Maine in relation to changes in selected prey. *Fish. Bull.* 88:687-696.

Pettigrew, N. R. 1994. The observational basis for subtidal circulation in the Gulf of Maine. In *Gulf of Maine Circulation Modeling: Workshop Proceedings*, Regional Association for Research on the Gulf of Maine, ed. E. Braasch , no. 94-1:3-19. Dartmouth College, Hanover, NH.

Plourde, S. and J. A. Runge. 1993. Reproduction of the planktonic copepod *Calanus finmarchicus* in the Lower St. Lawrence Estuary: relation to the cycle of phytoplankton production and evidence for a *Calanus* pump. *Mar. Ecol. Prog. Ser.* 102(3):217-227.

Polacheck, T., D. Mountain, D. McMillan, W. Smith, and P. Berrien. 1992. Recruitment of the 1987 year class of Georges Bank haddock (*Mellanogrammus aeglefinus*): the influence of unusual larval transport. *Can. J. Fish. Aquat. Sci.* 49: 484-496.

Sherman, K., J. R. Green, J. R. Goulet, and L. Ejsymont. 1983. Coherence in zooplankton of a large northwest Atlantic ecosystem. *Fish. Bull.* 81(4):855-862.

Sherman, K.. 1970. U.S. Fish. Wildlife Service, Special Scientific Report. Fish. No. 594. Washington, D.C., 8pp.

Smith, W. 1983. Temporal and spatial shifts in spawning of selected fish and invertebrate species in the Georges Bank region. NOAA/NMFS Laboratory Ref. SHL Report 83-08. 22 pp.

Smith, P. C. 1978. Low-frequency fluxes of momentum, heat, salt, and nutrients at the edge of the Scotian shelf. *J. Geophys. Res.* 83:4079-4406.

Sullivan, B. K. and L. T. McManus. 1986. Factors controlling seasonal succession of the copepods *Acartia hudsonica* and *A. tonsa* in Narragansett Bay, Rhode Island: temperature and resting egg production. *Mar. Ecol. Prog. Ser.* 28:121-128.

Sullivan, B. K. and C. J. Meise. 1996. Invertebrate predators of zooplankton on Georges Bank, 1977-1987. *Deep-Sea Res.* 43:1503-1519.

Toner, R. C. 1984. Zooplankton of western Cape Cod Bay. In *Observations on the Ecology and Biology of Western Cape Cod Bay, Massachusetts*, ed. J. D. Davis and D. Merriman, 65-76. Berlin: Springer-Verlag.

Townsend, D. W. 1984. Comparison of inshore zooplankton and ichthyoplankton populations of the Gulf of Maine. *Mar. Ecol. Prog. Ser.* 15:79-90.

Townsend, D. W. 1991. Influences of oceanographic processes on the biological productivity of the Gulf of Maine. *Rev. Aquat. Sci.* 5(3-4):211-230.

Townsend, D. W., T. L. Cucci, and T. Berman. 1984. Subsurface chlorophyll maxima and vertical distribution of zooplankton in the Gulf of Maine. *J. Plankton Res.* 6(5):793-802.

Townsend, D. W. and R. W. Spinrad. 1986. Early spring phytoplankton blooms in the Gulf of Maine. *Cont. Shelf Res.* 6(4):515-529.

Townsend, D. W., J. P. Christensen, D. K. Stevenson, J. J. Graham, and S. B. Chenoweth. 1987. The importance of a plume of tidally-mixed water to the biological oceanography of the Gulf of Maine. *J. Mar. Res.* 45:699-728.

Townsend, D. W., M. D. Keller, M. E. Sieracki, and S. G. Ackleson. 1992. Spring phytoplankton blooms in the absence of vertical water column stratification. *Nature* 360:59-62.

Turner, J. T. 1994. Planktonic copepods of Boston Harbor, Massachusetts Bay and Cape Cod, 1992. *Hydrobiologia* 293:405-413.

U.S. Fish. Wildlife Service. 1970. *Seasonal and areal distribution of zooplankton in coastal waters of the Gulf of Maine, 1967 and 1968* by K. Sherman. Special Scientific Rep. Fish. No. 562. Washington, D.C., 11 pp.

Walford, L. A. 1938. Effects of currents on distribution and survival of the eggs and larvae of haddock (*Mellanogrammus aeglefinus*) on Georges Bank. *Fish. Bull. U.S.* 49:1-73.

Wang, S. B. and E. D. Houde. 1995. Distribution, relative abundance, biomass and production of bay anchovy *Anchoa mitchilli* in the Chesapeake Bay. *Mar. Ecol. Prog. Ser.* 121(1-3):27-38.

Wishner, K., E. Durbin, A. Durbin, M. Macaulay, H. Winn, and R. Kenney. 1988. Copepod patches and right whales in the Great South Channel off New England. *Bull. Mar. Sci.* 43(3):825-844.

Wishner, K. F., J. R. Schoenherr, R. Beardsley, and C. Chen. 1995. Abundance, distribution and population structure of the copepod *Calanus finmarchicus* in a springtime right whale feeding area in the southwestern Gulf of Maine. *Cont. Shelf Res.* 15(4-5):475-507.

Woodley, T. H. and D. E. Gaskin. 1996. Environmental characteristics of North Atlantic right and fin whale habitat in the lower Bay of Fundy, Canada. *Can. J. Zool.* 74(1):75-84.

Yentsch, C. S. and N. Garfield. 1981. Principal areas of vertical mixing in the waters of the Gulf of Maine, with reference to the total productivity of the area. In *Oceanography from Space*, ed. J. F. R. Gower, 303-312. New York: Plenum.

Zillioux, E. J. and J. G. Gonzalez. 1972. Egg dormancy in a neritic calanoid copepod and its implications to overwintering in boreal waters. In *Fifth European marine biology symposium*, ed. B. Battaglia, 217-230. Padova: Piccin Editore.

Vertical Exchange Processes in the Gulf of Maine

Peter C. Smith
Bedford Institute of Oceanography

Abstract

Recent advances in our understanding of vertical exchange mechanisms in the Gulf of Maine and their influence on nutrient transport, primary production and higher trophic levels are reviewed. Observational studies include an extensive series of hydrographic and moored measurements (Brown and Irish, 1993) during 1986-87 which were used to identify processes leading to deep winter mixing (to >200m) in the western Gulf, resulting in the formation of large quantities of Maine Intermediate Water. A large interannual difference was noted between the quantities of Maine Intermediate Water formed in 1986-87 versus 1985-86, when volumes were much reduced. Stratified tidal rectification and tidal mixing are also found to induce significant vertical fluxes of mass, heat, salt and nutrients. Off Cape Sable, Nova Scotia, topographic upwelling is driven by tidally-induced cross-isobath flow on the eastern side of the Cape and produces the exceptionally low summer surface temperatures and high nutrient concentrations in the region. Circulation studies on the northern flank of Georges Bank also show a complex system of interacting barotropic, and baroclinic tides, hydraulic jumps and internal waves. Vertical mixing associated with breaking internal waves and the tidal front is (arguably) sufficient to support the nitrate demand of the frontal zone. As a result, "new" primary production (f-ratio) and zooplankton abundances peak at the tidal front and the bank edge in summer. Extensive coastal upwelling is also observed on the Scotian Shelf in response to persistent favorable longshore winds. In the mature phases of this process, the upwelling front deforms into a series of cold surface plumes (extending up to 175 km from the coast with 50-75 km spacing) that have been attributed to baroclinic instability.

A variety of numerical models have been developed to simulate and interpret some of the observed vertical exchange mechanisms. Process models, idealized to focus on a particular aspect of the circulation, provide useful insights into topographic upwelling, wind-driven upwelling, stratified tidal rectification, and internal wave generation. A comprehensive 3-D model, designed to encompass most of the important physical processes in the Gulf also provides realistic simulations of the climatological seasonal cycle for the entire region. The tidal rectification process model and the comprehensive 3-D model have been used to address important biological issues such as the origin of the vertical fluxes of nutrients that support "new" production on the northern flank of Georges Bank and the seasonal routes for zooplankton (*Calanus finmarchicus*) from the Gulf of Maine to the Bank. A future challenge for this research in the Gulf of Maine is the continued pursuit of model-assisted studies which blend the theoretical and observational approaches. Research topics related to vertical exchange mechanisms include:

1. storm response in the western Gulf,
2. further improvements to biological/physical models of tidal fronts, and
3. shelf/slope water interactions.

Introduction

With some of the world's highest tides and a confluence of cold fresh northern waters and nutrient-rich offshore waters, the Gulf of Maine supports several thriving ecosystems which are both complex and diverse. Since the nutrient supply to the lowest trophic levels of these systems is generally found in the deep slope waters, efficient vertical exchange mechanisms are vital to sustaining the high levels of productivity in the surface layers. A plethora of physical processes produce these exchanges at time scales of minutes to months and horizontal scales of 100m to 100km. This review will focus on recent advances in our understanding of these mechanisms and their influence on nutrient transport, primary production and higher trophic levels. In particular, new observations of the vertical exchange processes associated with winter overturning, tidal mixing and fronts, internal waves and wind-driven upwelling will be summarized; recently-developed numerical circulation models related to these processes will be described; the biological significance will be discussed; and conclusions will be presented.

Recent Observations

Winter Overturning in the Western Gulf of Maine

Bigelow (1927) was the first to recognize that local winter cooling and the constraints of geography were responsible for the production of a seasonal (late spring-fall), cold intermediate water mass in the Gulf of Maine. He also identified the coastal zone in the western Gulf of Maine as the region where intense vertical exchange occurs to mix the atmospherically-cooled surface waters with warmer, saltier bottom waters that enter the Gulf through Northeast Channel. In their analysis of historical hydrographic data from the 1960s - 70s, Hopkins and Garfield (1979) labeled this water mass Maine Intermediate Water and demonstrated that it was not only produced locally, but also exported in significant quantifies from the Gulf over the summer months. Their analysis indicated that the late summer remnant of Maine Intermediate Water lies primarily over Wilkinson Basin.

In the winter of 1974-75, Brown and Beardsley (1978) attempted to monitor the effects of deep convective overturning in the western Gulf through a series of ten 1-day hydrographic cruises conducted between the passage of strong winter storms. Their results clearly demonstrated that cold, dry offshore winds drive deep mixing processes similar to those associated with the Mistral winds in the Western Mediterranean (e.g., Stommel, 1972) or with winter continental winds over the western Labrador Sea (e.g., Gascard and Clarke, 1983; Clarke and Gascard, 1983). The primary zone of temperature-induced overturning occurs between the 100 and 150m isobath, i.e. outside of the frontal boundary associated with the coastal buoyancy current, in a region "preconditioned" for deep convection by a series

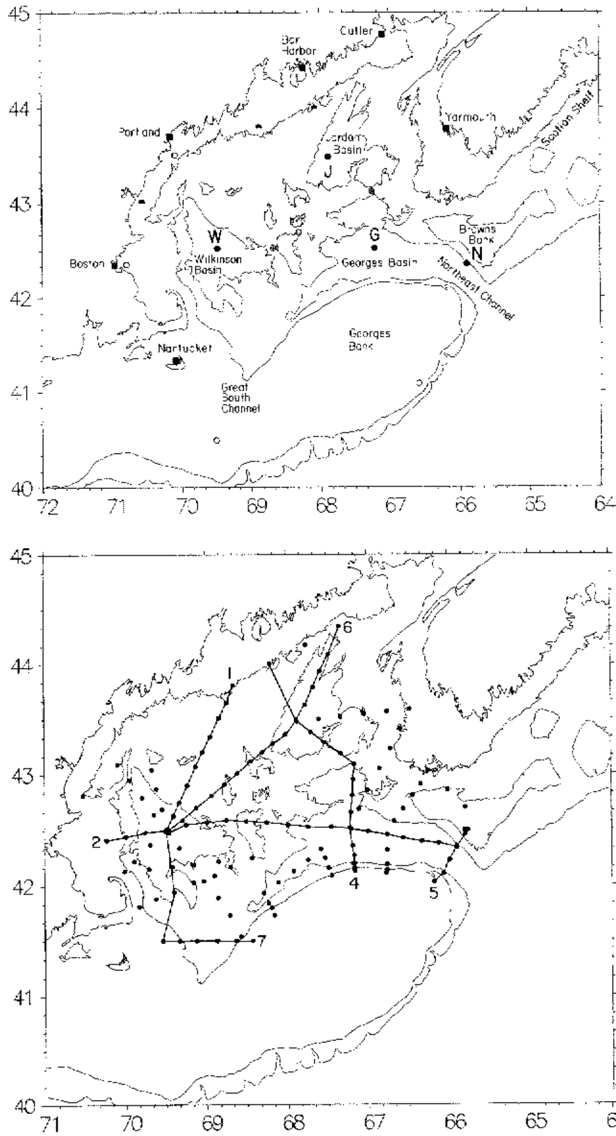


Figure 1. Location map for Brown and Irish's (1993) (a) moored and coastal array (top), and (b) typical hydrographic survey for their 1986-87 experiment (bottom). In (a) are found temperature/conductivity/bottom pressure instrumentation (solid circles), coastal sea level stations (solid squares), NDBC meteorological buoys (open circles), and USGS long-term near bottom current meter sites (crossed circles). In (b), hydrographic stations and selected vertical sections are identified.

of intermediate mixing events in autumn and early winter. Vertical profiles of density near the leading edge of the mixing zone were observed to be statically unstable over the top 60m, strongly indicating the potential for vertical exchange. In an attempt to quantify the air-sea

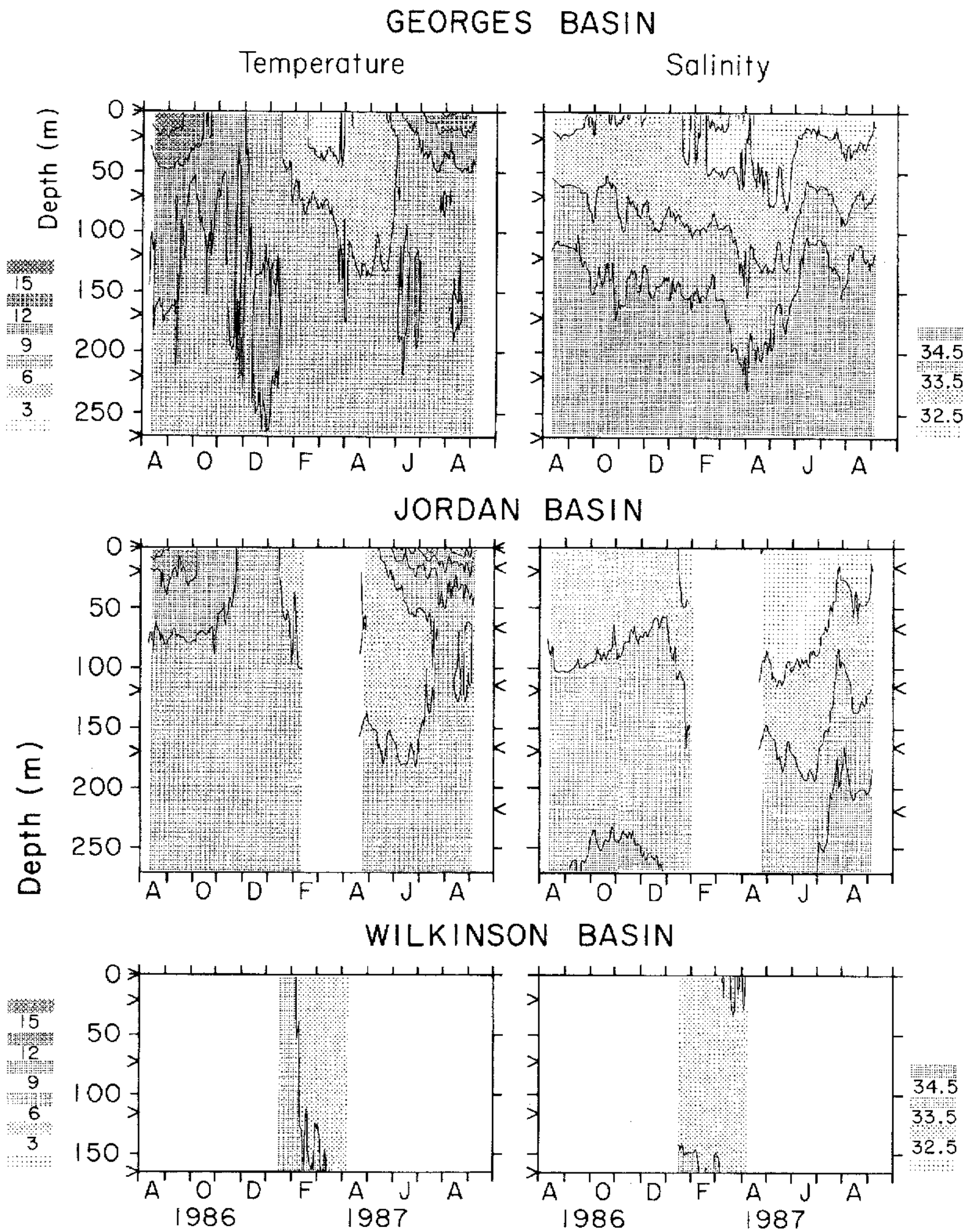


Figure 2. The evolution of seasonal profiles of temperature (left) and salinity (right) derived by linear interpolation of adjacent subtidal time series measurements on the Georges, Jordan and Wilkinson Basin moorings (Brown and Irish, 1993).

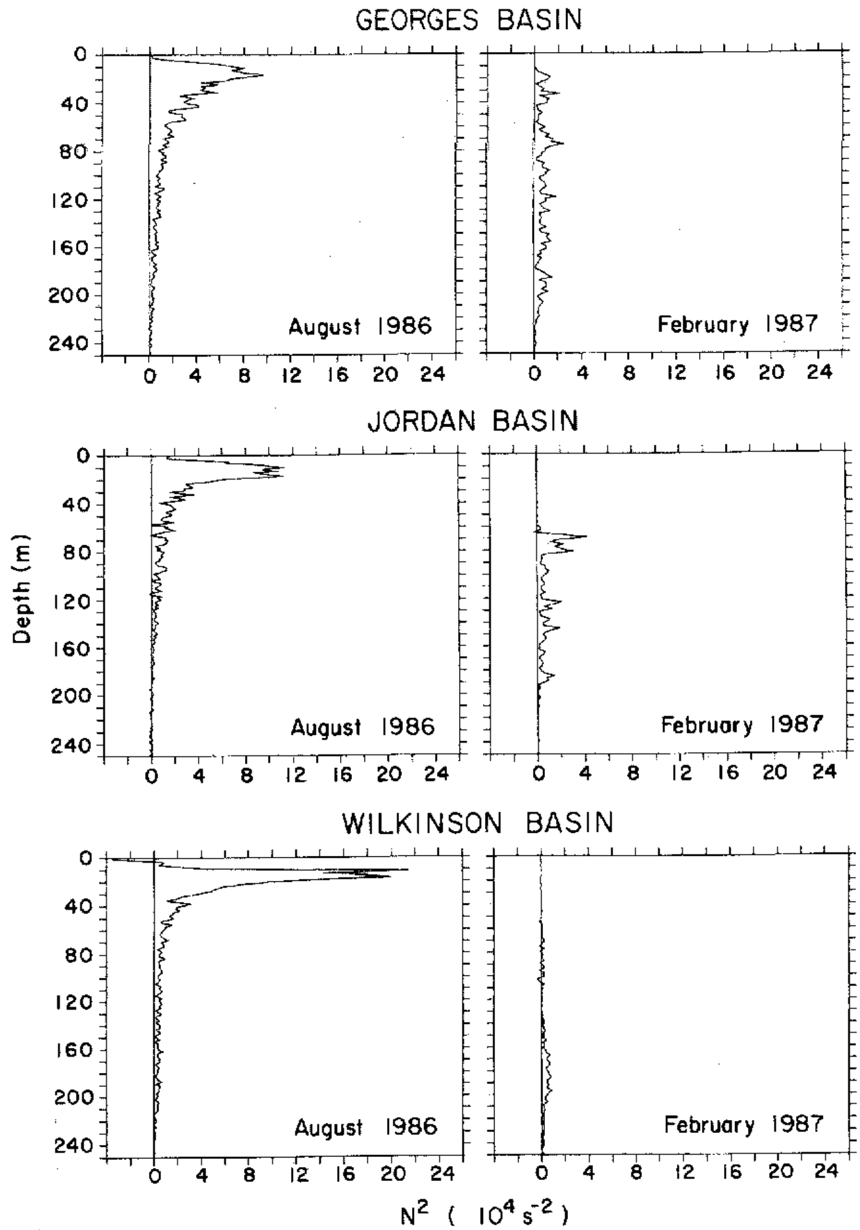


Figure 3. Stratification (N^2; buoyancy frequency) profiles in three major basins from CTD averages in August 1986 (maximum) and February 1987 (minimum). (Brown and Irish, 1993).

exchange process itself, Brown and Beardsley (1978) compared the cumulative heat loss estimated from Portland Lightship data to the observed temporal changes in water column heat content from the hydrographic measurements. Although a significant discrepancy (65 Wm^{-2}) was found between these estimates [not surprising considering the short spatial scales on which the atmospheric boundary layer adjusts to sharp changes in surface boundary conditions; Smith and MacPherson, (1987)], the visual similarity of the two did suggest that air-sea exchange is the principal component of the heat budget in this region.

More recently, Brown and Irish (1993) have used an extensive series of hydrographic and moored measurements to identify and interpret the annual variation of the water mass structure in the Gulf during 1986-87. These data consist of time series of coastal sea level and meteorological observations, offshore meteorological buoy measurements, and moored measurements of temperature/conductivity/bottom pressure in each of the primary basins of the Gulf (Figure 1a), as well as five extensive conductivity-temperature-depth (CTD) surveys between August, 1986 and September, 1987 (Figure 1b). Although hampered by the loss of the Wilkinson Basin mooring for most of the experiment, the interpolated versions of the moored hydrographic time series (Figure 2) reveal the early winter preconditioning of the water columns for deep convection in both Jordan and Wilkinson Basins. Furthermore comparison of stratification profiles in all three basins, August vs. February (Figure 3), indicates that the preconditioning process is less effective in the eastern (e.g., Jordan Basin) than the western (Wilkinson Basin) Gulf, primarily because of the strong influx of fresh Scotian Shelf water to the eastern Gulf at that time (Smith, 1983). The 130m depth of the mixed layer (i.e. $N^2 \cong 0$) is convincing evidence

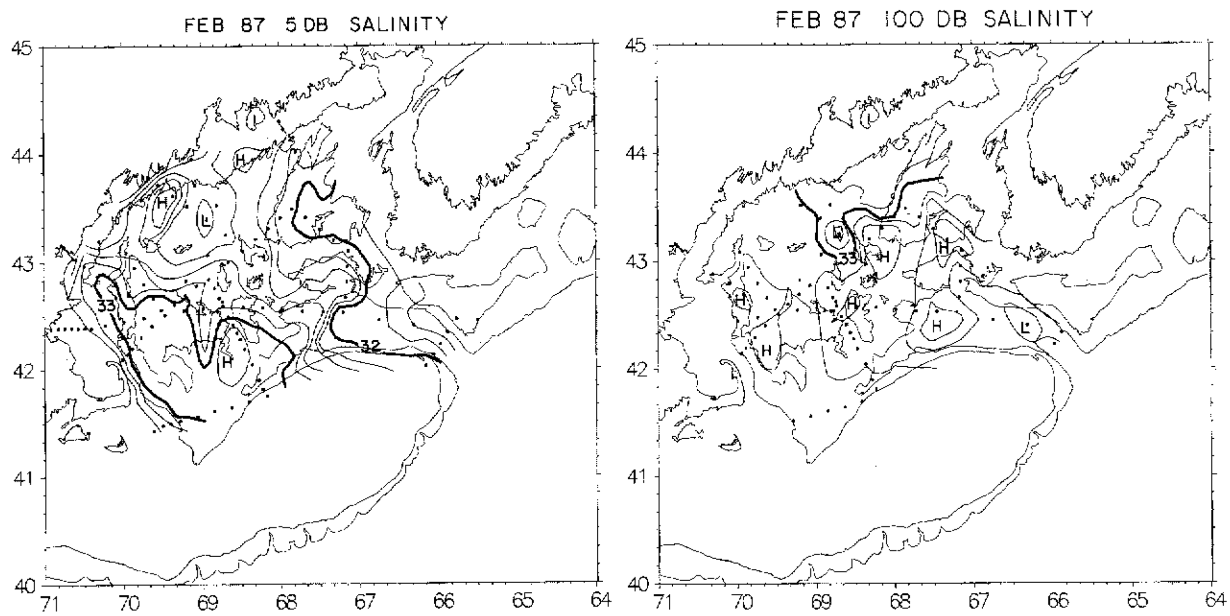


Figure 4. Maps of salinity on 5db and 100db surfaces during 5-20 February, 1987. Contour interval is 0.2ppt. (Brown and Irish, 1993).

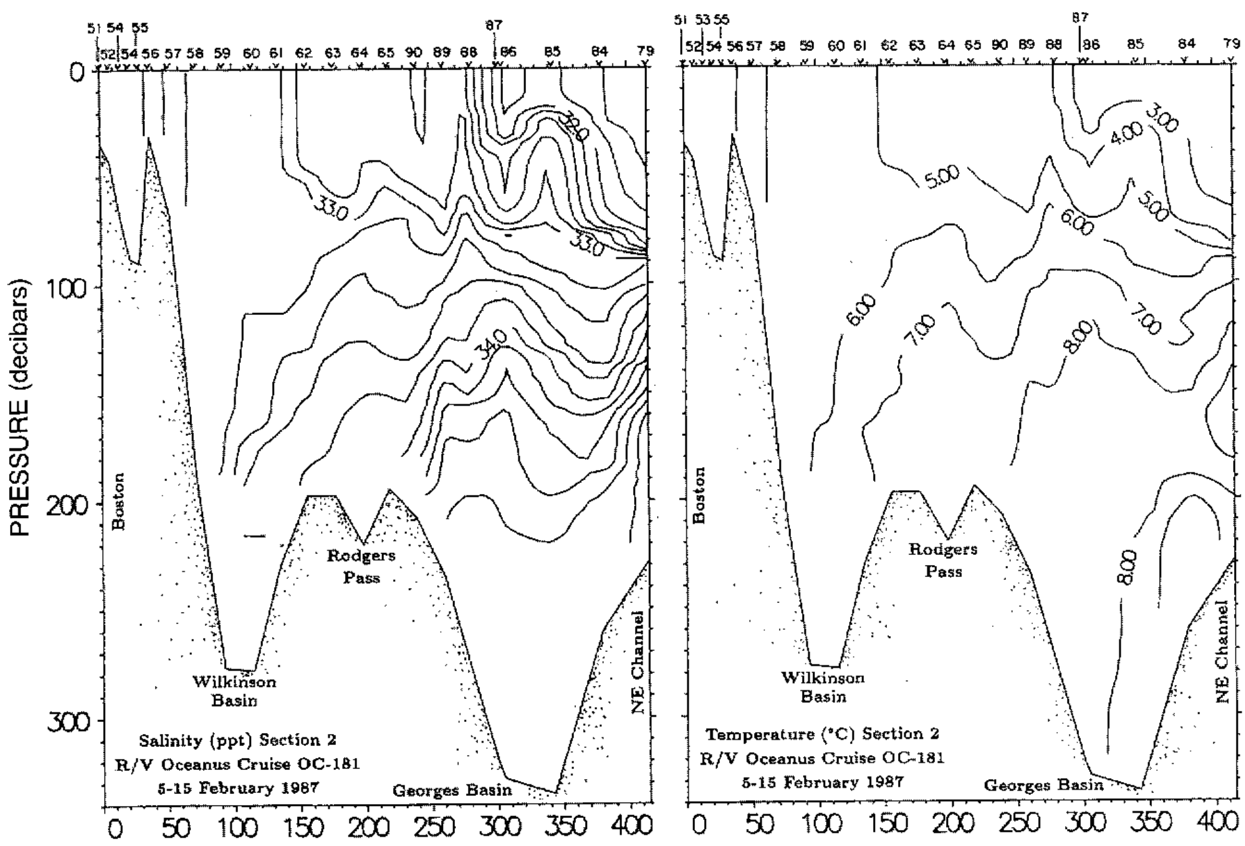


Figure 5. Temperature (right) and salinity (left) on Section 2 (Figure1b) during February, 1987. Contour intervals are 1°C and 0.2ppt, respectively. (Brown and Irish, 1993).

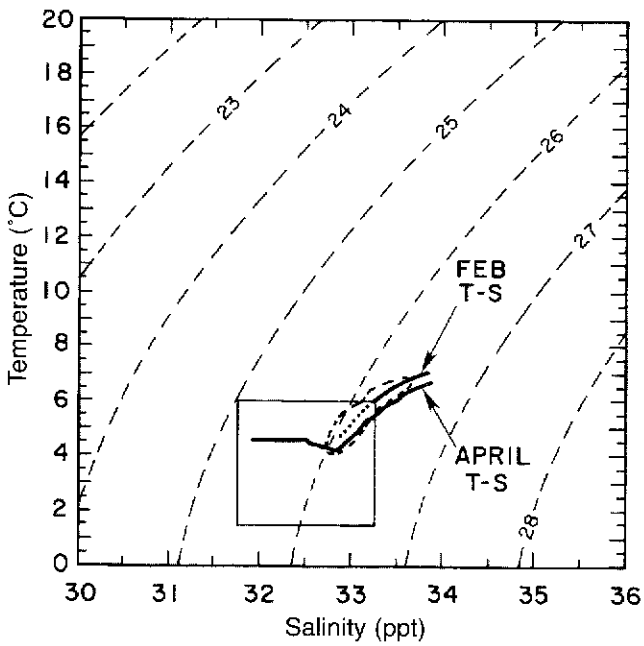


Figure 6. A comparison of temperature-salinity relationships from moored and shipboard observations in Wilkinson Basin during winter and early spring 1987. The dashed line is the envelope of subtidal moored data; CTD traces are for February 7 (solid) and 15 (solid plus dot) and April near the mooring; and the box defines 1987 Maine Intermediate Water properties. (Brown and Irish, 1993).

that deep mixing occurs preferentially in Wilkinson Basin. Brown and Irish's (1993) measurements also provided a clearer synoptic picture of the winter water production process. Examination of the near-surface (5 db) and deep (100 db) salinity maps for February 1987 (Figure 4) reveals a patchy distribution in the inshore regions of both Jordan and Wilkinson Basins. This effect is considered to be the signature of localized convective mixing and entrainment under variable winter winds. Furthermore, the reduced stability in Wilkinson Basin during this particular year leads to mixed layers approaching 200 m depth (Figure 5). A more direct inference of this process is made by comparing the T-S traces from two February (7th and 15th) and one April CTD casts with the property envelope derived from instruments on the nearby Wilkinson Basin mooring (Figure 6). The two February casts reveal an intrusion of colder, fresher (and lighter) water with Maine Intermediate Water properties following the passage of a severe winter storm on February 11th. Continued cooling between February and March resulted in the downward expansion of the temperature-salinity (T-S) property envelope, sig-

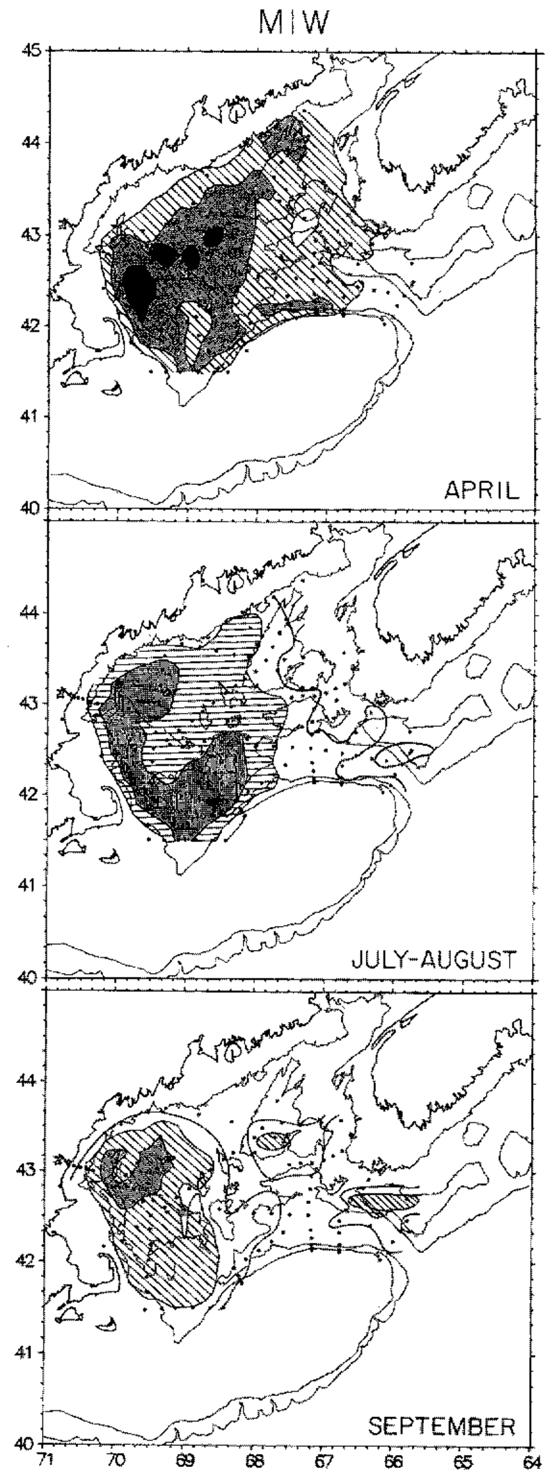


Figure 7. Evolution of distribution of Maine Intermediate Water thickness from April to September, 1987. Only thicknesses deeper than 40m are shown for April. Thickness ranges are 0-50m (clear), 50-100m (hatched), 100-150m (stippled) and > 150m (solid). (Brown and Irish, 1993).

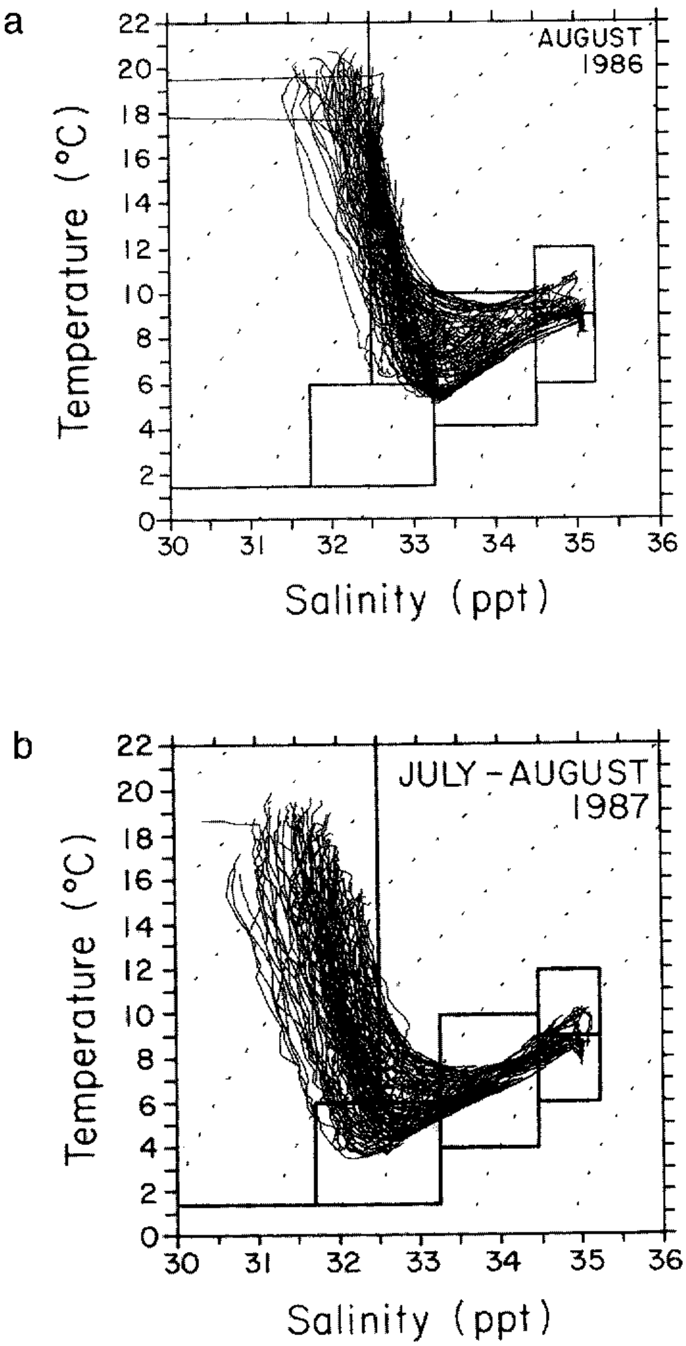


Figure 8. Comparison of composite T-S relationships from (a) August 1986 and (b) July-August 1987. Northeast Channel stations have been excluded. The superimposed rectangles (in order of increasing salinity) represent properties of 1987 Maine Surface Water (MSW), Maine Intermediate Water (MIW), Maine Bottom Water (MBW), Warm Slope Water (WSW) and Labrador Slope Water (LSW). (Brown and Irish, 1993).

naling significant production of Maine Intermediate Water.

The evolution of the Maine Intermediate Water distribution through the spring and summer of 1987 is depicted in Figure 7. The net result is a loss of nearly 60% of the Maine Intermediate Water volume through export and mixing. Results of a simple water mass conservation model (Brown and Irish, 1993) suggest that more than 70% of this volume is exported from the Gulf while roughly 30% is lost through mixing to produce other water masses. These figures differ significantly from those derived by Hopkins and Garfield (1979), using a different approach and different data base, which may be indicative of strong interannual variability in Maine Intermediate Water production and transport, as suggested by Mountain and Jessen (1986).

The interannual variability in Maine Intermediate Water production is clearly exhibited by the difference between Brown and Irish's (1993) Gulf-wide composite T-S relations (Figure 8) for August 1986 and 1987. The much larger volume of Maine Intermediate Water in 1987 implies a richer supply of nutrients to both Georges Bank (Hopkins and Garfield, 1981; Flagg, 1987), via "leakage" from the export current in spring and summer, and to the coastal zone in the western Gulf via upwelling from the remnant reservoir in autumn. Mountain and Jessen (1987) suggest that the potential for deep convection in Wilkinson Basin is conditioned not only by meteorological forcing in the autumn, but also by relatively high surface salinities (>33) around the edges of the basin which allow surface densities to exceed those near the bottom with only moderate amounts of cooling. Thus vertical exchange processes are controlled not only by the severity of the winter but also by the previous year's rate of freshwater input.

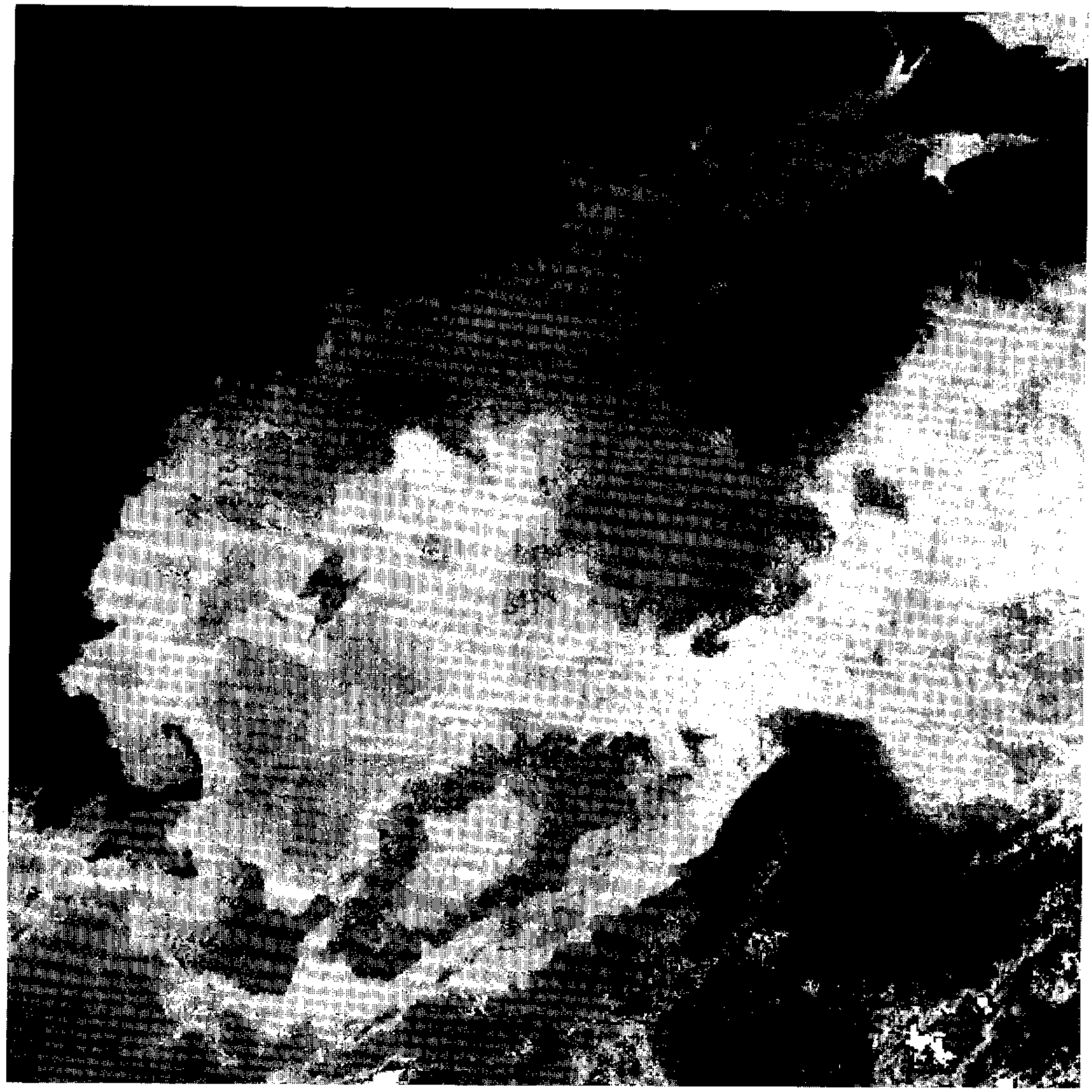


Figure 9a. Satellite infrared SST image of Gulf of Maine from 27 August, 1984. Cool temperatures caused by tidal mixing and advection are found over Nantucket Shoals, Georges Bank, off southwest Nova Scotia and from the Bay of Fundy down the Maine coast. Coldest temperatures are found off Cape Sable, Nova Scotia and in the Bay of Fundy; a cool frontal band surrounds the Georges Bank "hot spot".

Tidal Mixing and Fronts

In summer and early autumn, the general location of tidally well-mixed areas, bounded by tidal fronts, may be identified from a clear satellite infrared image of the sea surface temperature (Figure 9a). The cool band surrounding Georges Bank, for instance, marks the location of the tidal front containing a warmer central core ("hot spot") on the cap of the Bank. Other frontal zones lie off southwest Nova Scotia, in the Bay of Fundy, along the Maine coast from Grand Manan Island to Penobscot Bay and over Nantucket Shoals off Cape Cod. These positions are roughly consistent with frontal boundaries (Figure 9b) predicted by an empirical vertical mixing criterion based on the assumptions that

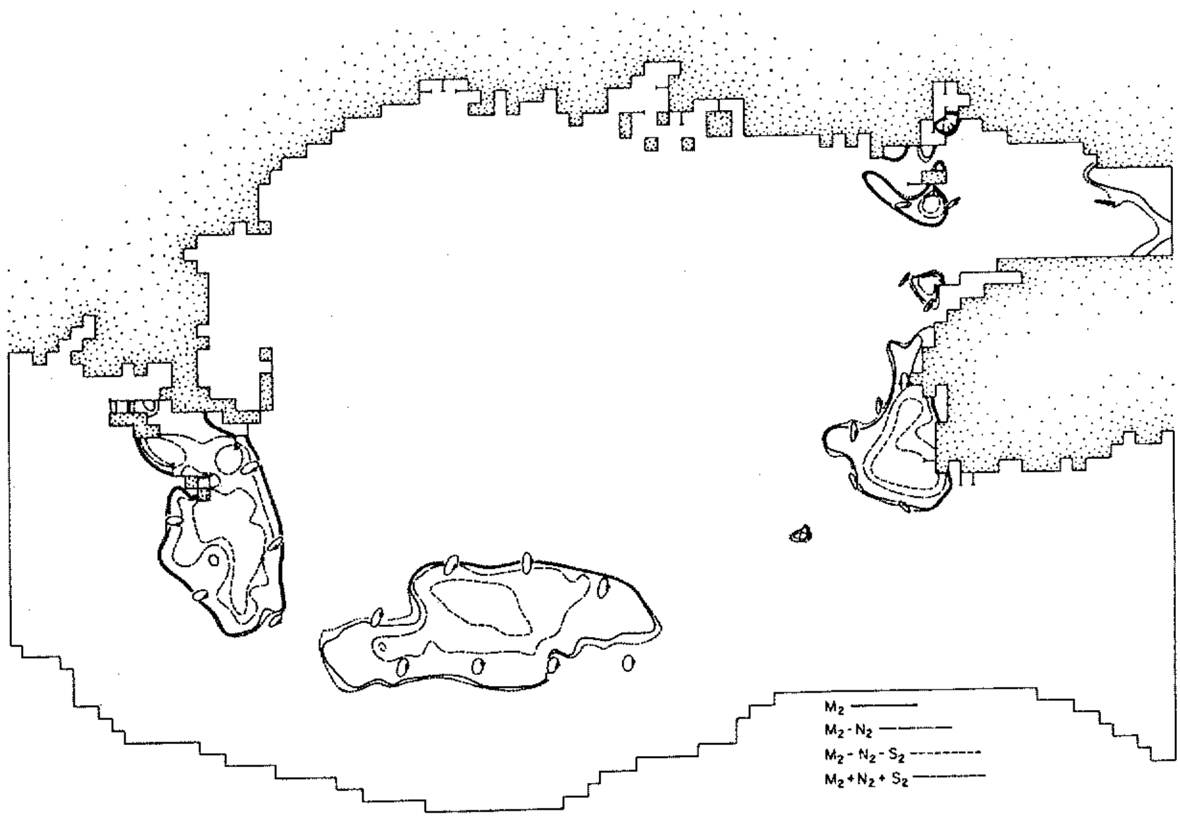


Figure 9b. Predicted positions of tidal fronts, based on empirical mixing criterion (Loder and Greenberg, 1986), for M_2 currents only and various spring-neap maxima and minima. The tidal ellipses in the vicinity of the fronts are also shown.

1) the surface heat flux; Q, is the sole buoyancy source, and 2) a fixed fraction of the depth-integrated dissipation rate by tidal currents is available for work against gravity (Simpson and Hunter, 1974; Garrett et al., 1978). Loder and Greenberg (1986) have estimated those frontal positions using a fine-grid (7 x 7 km) numerical tidal model, and also investigated the variability of those positions associated with monthly and fortnightly variations of tidal mixing (Figure 9b), additional wind mixing, and the introduction of different physical assumptions about the mixing processes. In general there is good agreement between model and observed frontal boundaries. Major discrepancies (such as found along the Maine coast) are ascribed to wind-driven upwelling and/or horizontal displacement by mean currents.

However, despite the apparent success of such simple physical criteria and models, recent observations suggest that the detailed physics of the mixing zones are quite complex and difficult to quantify, primarily because of tidally-induced residual currents in and around the mixing zone. The following subsections summarize recent findings on 1) topographic upwelling off southwest Nova Scotia, 2) monthly and fortnightly modulation of the tidal front on the southern flank of Georges Bank, and 3) mixing processes on the northern flank of Georges.

Topographic Upwelling off Southwest Nova Scotia

One of the more obvious contrasts in the distribution of summer sea surface temperature (SST) as observed by satellite (Figure 9a) is between the core temperatures on Georges Bank (16-17°C) and those off Cape Sable, Nova Scotia (7-9°C). Early theories attributed the observed upwelling currents off southwest Nova Scotia (e.g., Lauzier, 1967) to centrifugal forces associated with the strong tidal flows (Garrett and Loucks, 1976) and later baroclinic forces maintained by longshore variations in tidal mixing (Smith, 1983). However, Tee, et al. (1993) have recently used observations and inferences from a regional tidal model (Tee, 1979, 1980, 1987, Tee et al.,

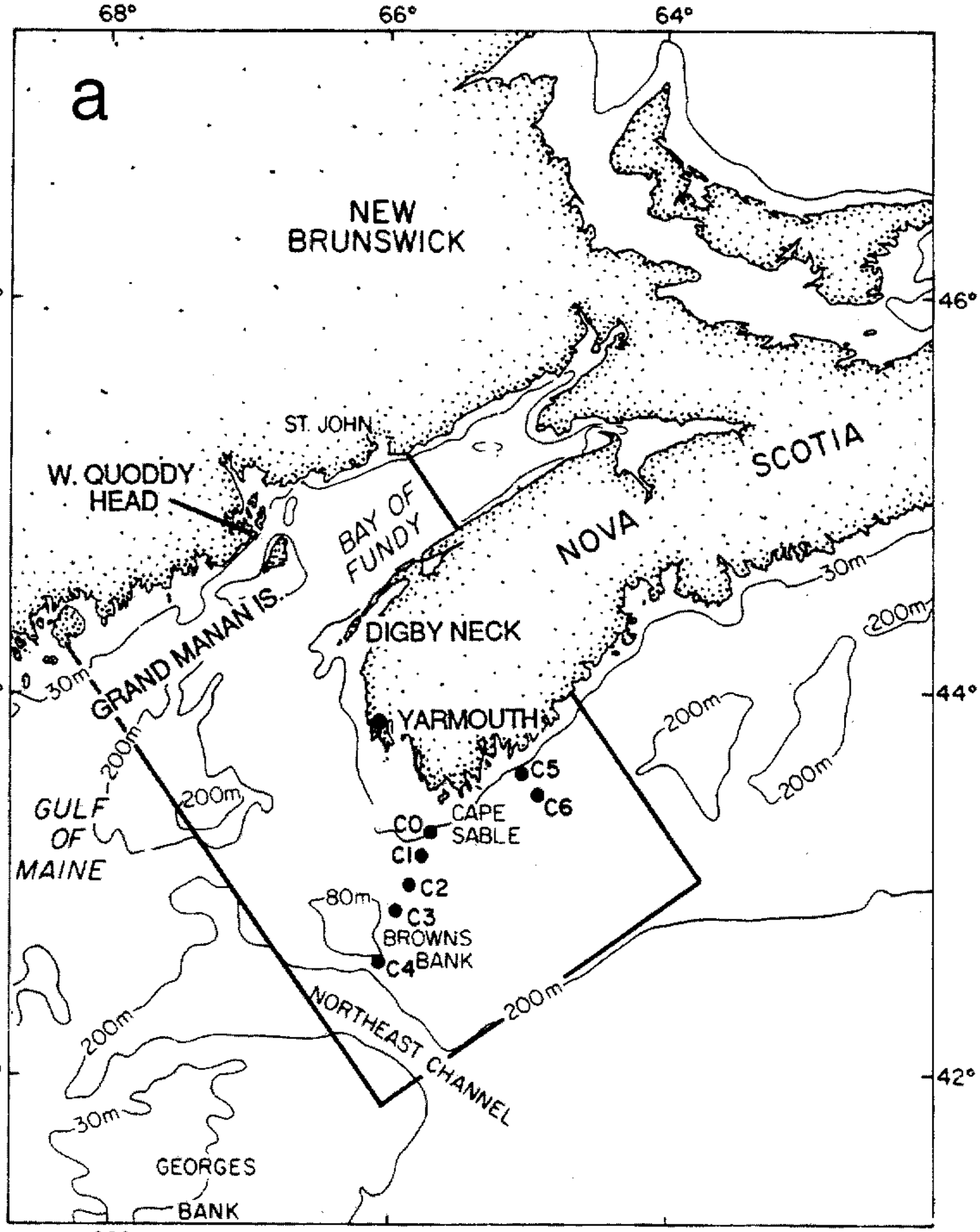


Figure 10a. Location map for regional tidal model of Bay of Fundy and eastern Gulf of Maine (Tee et al., 1993).

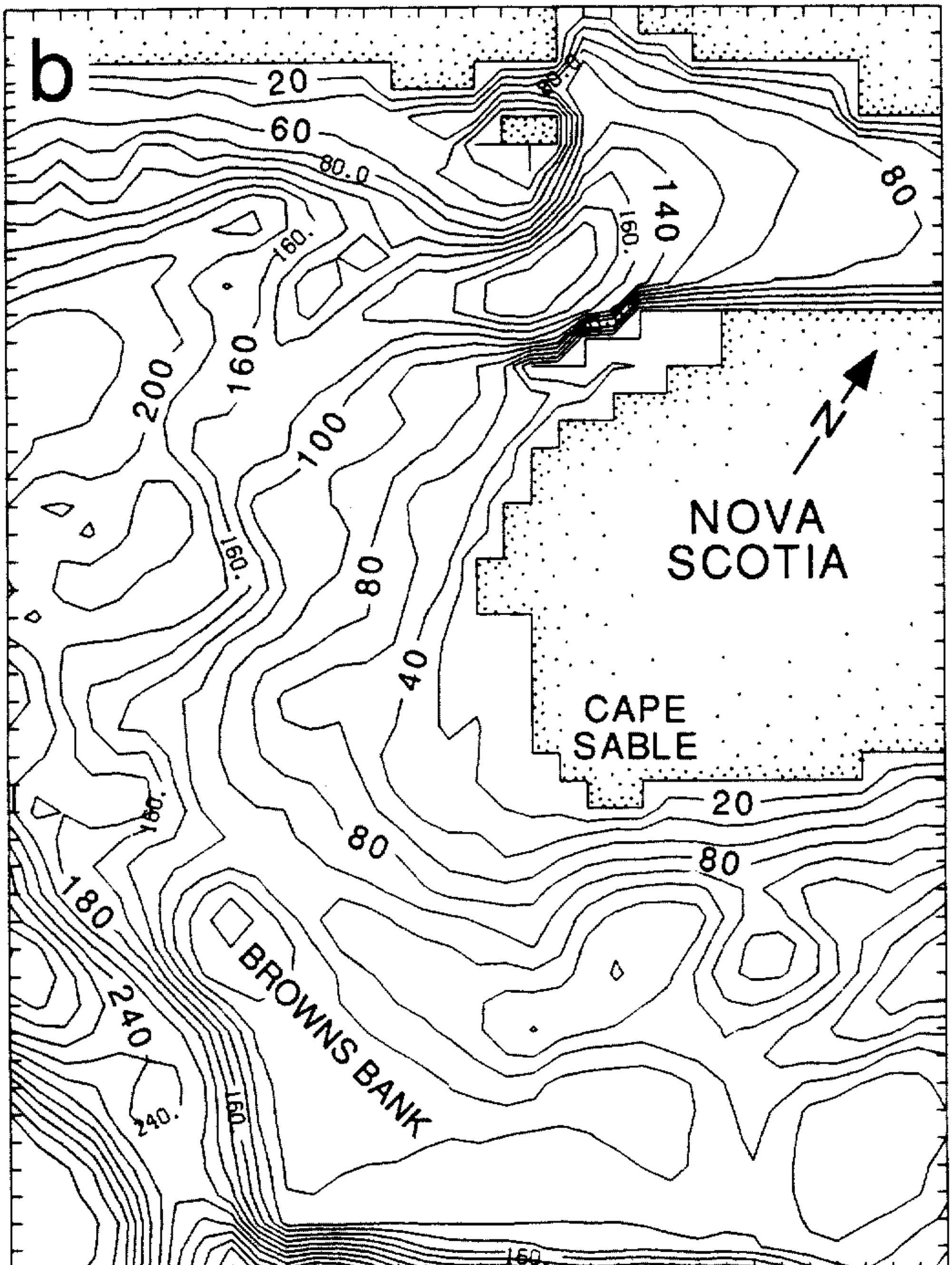


Figure 10b. Model topography. Grid spacing (7.05 km) is indicated by boundary tick marks.

1987, 1988; Figure 10) to demonstrate that both the location and strength of the sea surface temperature (SST) anomaly off Cape Sable are controlled primarily by the combination of tidal mixing and a 3-D rectification process, called "topographic upwelling", associated with tidal flow over complex bottom topography.

Topographic upwelling differs from classical 2-D upwelling in that it requires the depth-averaged cross-isobath transport to be non-zero, so that convergences (divergences) of this flux are balanced by divergences (convergences) of the along-isobath transports. Cross-isobath transport toward shallower water to the east Cape Sable (Figure 11a) induces upwelling throughout the water column and, consequently, acceleration of the along-isobath flow (Figure 11b). Conversely, transport to deeper water west of Cape Sable causes downwelling and deceleration. Similar upwelling and downwelling zones exist around the edges of Browns Bank at somewhat smaller scales. The close correlation between cross-isobath flow and the upwelling also requires that the residual flow vary smoothly with depth, as has been observed (Tee et al., 1987).

As a basis of comparison, Tee et al. (1993) estimate that the strength of topographic upwelling on the eastern side of Cape Sable is equivalent (per unit long-shore distance) to 2-D coastal upwelling in response to a 7 ms^{-1} alongshore wind, which is almost three times the summer average over the Scotian Shelf (Petrie et al., 1987).

The cross-isobath transport of fluid columns causes them to shorten (lengthen) as they move to shallower (deeper) regions, but does not require vertical mixing. Thus a stratified water column from the Scotian Shelf could pass over the ridge off Cape Sable without significant changes to its surface properties. However, this shallow region is also one of high tidal dissipation which satis-

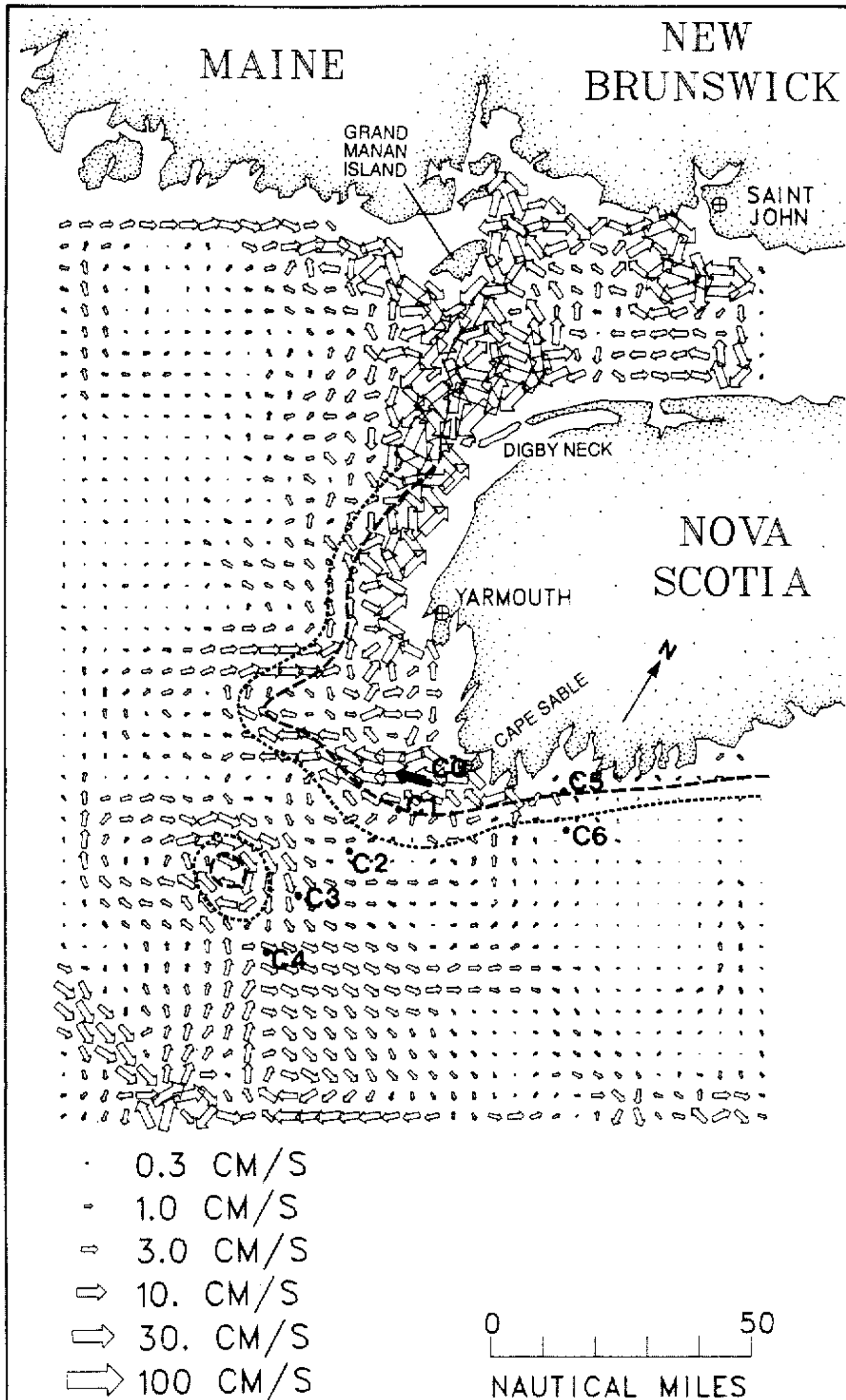


Figure 11a. Model depth-averaged currents induced by M_2 tide (Tee et al., 1993). The 60 and 80m isobaths, historical current meter mooring sites (C0-C6), and observed tidally-induced residual current at C0 are shown.

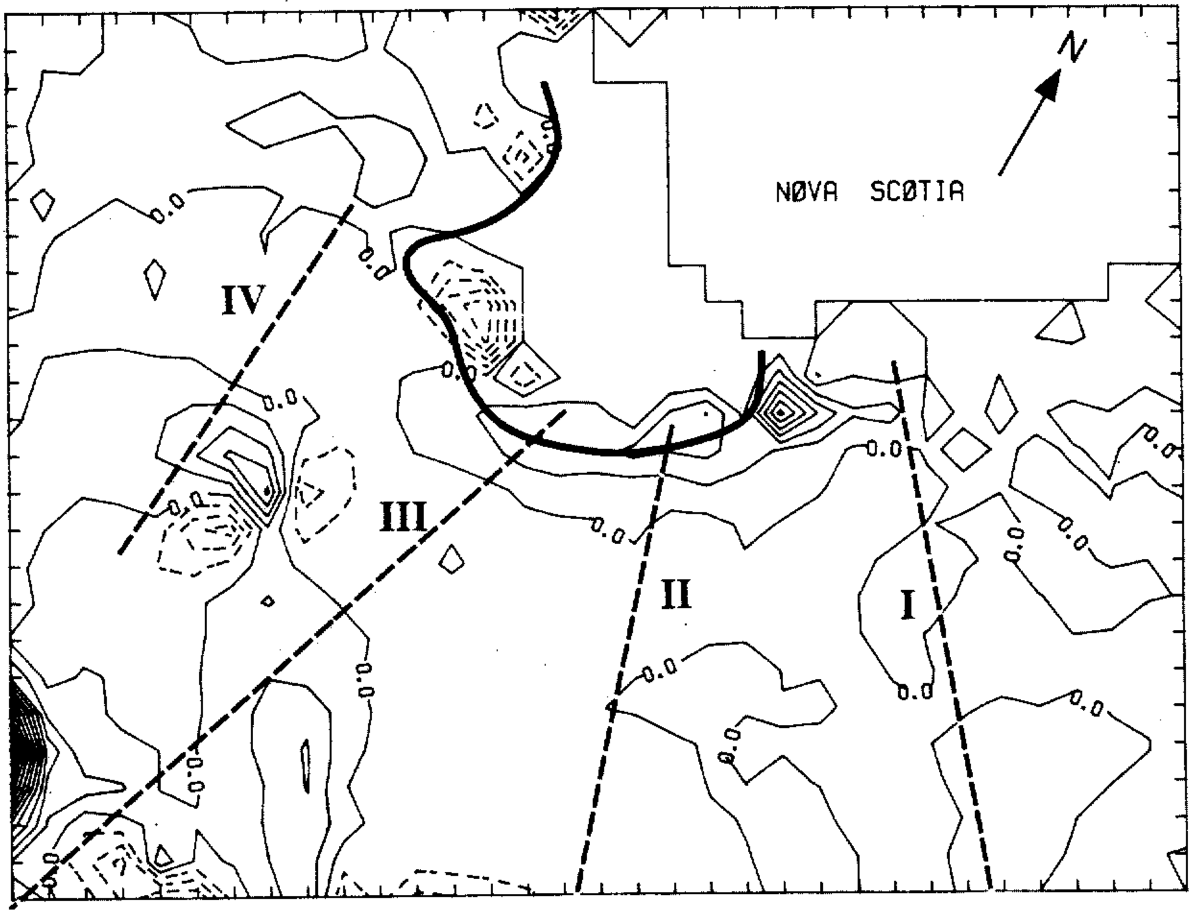


Figure 11b. Superposition of model residual vertical velocity (10^{-5} m s^{-1}), four hydrographic sections (I-IV), and predicted tidal front position (thick solid; Loder and Greenberg, 1986).

fies Loder and Greenberg's (1986) 1-D criterion for complete vertical mixing. In an advective setting, the essential question is how does the time scale for vertical mixing ($\tau_v = D^2/K_v$) compare with that for horizontal advection ($\tau_H = L/U$). Using measured residual currents ($U \cong 0.1$ ms^{-1}), a reasonable horizontal dimension (L = 50 km), a depth of D=40m and vertical eddy viscosity ($K_v = 0.03$ m^2s^{-1}) based on published formulae, Tee et al. (1993) found that $\tau_v/\tau_H \cong 0.1$. Hence water columns passing into the Cape Sable area are rapidly homogenized. Moreover, the reason for the absence of a low surface temperature zone over Browns Banks, in spite of the indication of strong mixing on the cap (Figure 9b), is that no single water column spends enough time there to become well mixed, i.e., $\tau_v/\tau_H \geq 1$.

Also central to the explanation of the sources and richness of the water in the upwelling zone is the observation that depth-averaged temperature, salinity and nitrate concentration are approximately conserved for water columns advecting through the region, i.e., $\frac{d\bar{T}}{dt} \approx \frac{d\bar{S}}{dt} \approx \frac{d\bar{N}}{dt} \approx 0$, where $\left(\frac{d}{dt} = \frac{\partial}{\partial t} + U_2 \bullet \nabla\right)$, U_2 is the depth-averaged residual current, and $(\bar{\ }) = \frac{1}{D}\int_{-D}^{0} (\cdot)dz$ is the depth-average operator for temperature (T), salinity (S), and nitrate (N). The basis for these arguments is that the estimated time scales for surface buoyancy input and nitrogen uptake in the mixed zone are significantly **longer** than the advective time scale (τ_H = 6-12 days). Hydrographic observations from the summer of 1979 (Figure 12a-d — next page) show the edge of the well-mixed zone (Station 10, Figure 12b) and indicate that the intermediate waters (50 - 100m) get progressively warmer in the westward direction, such that no water

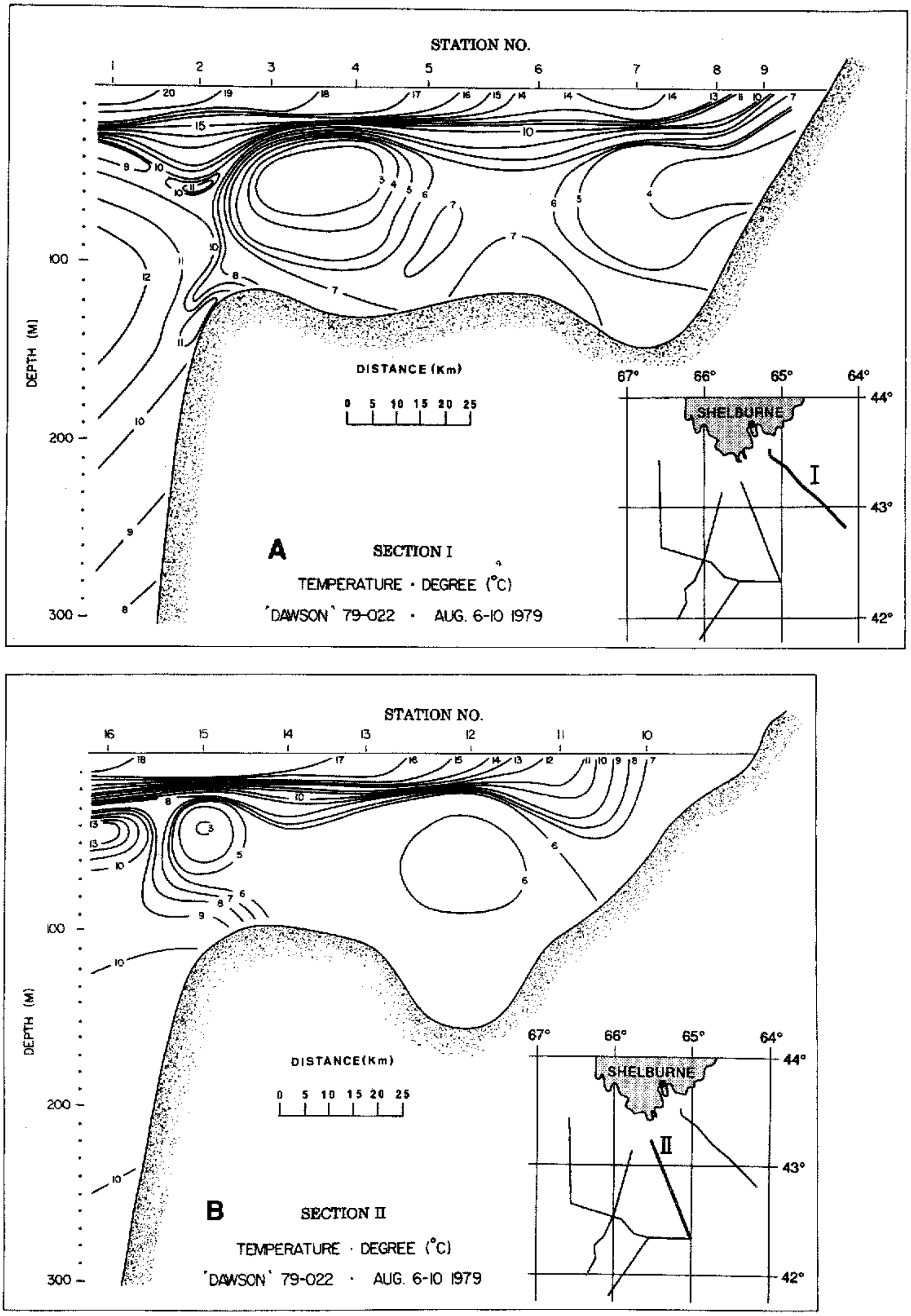
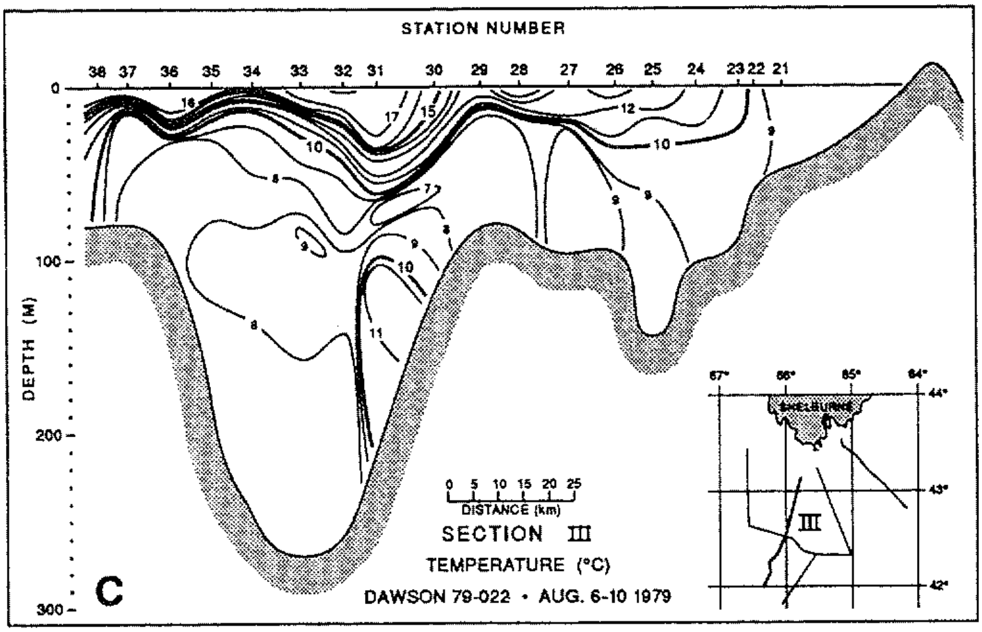
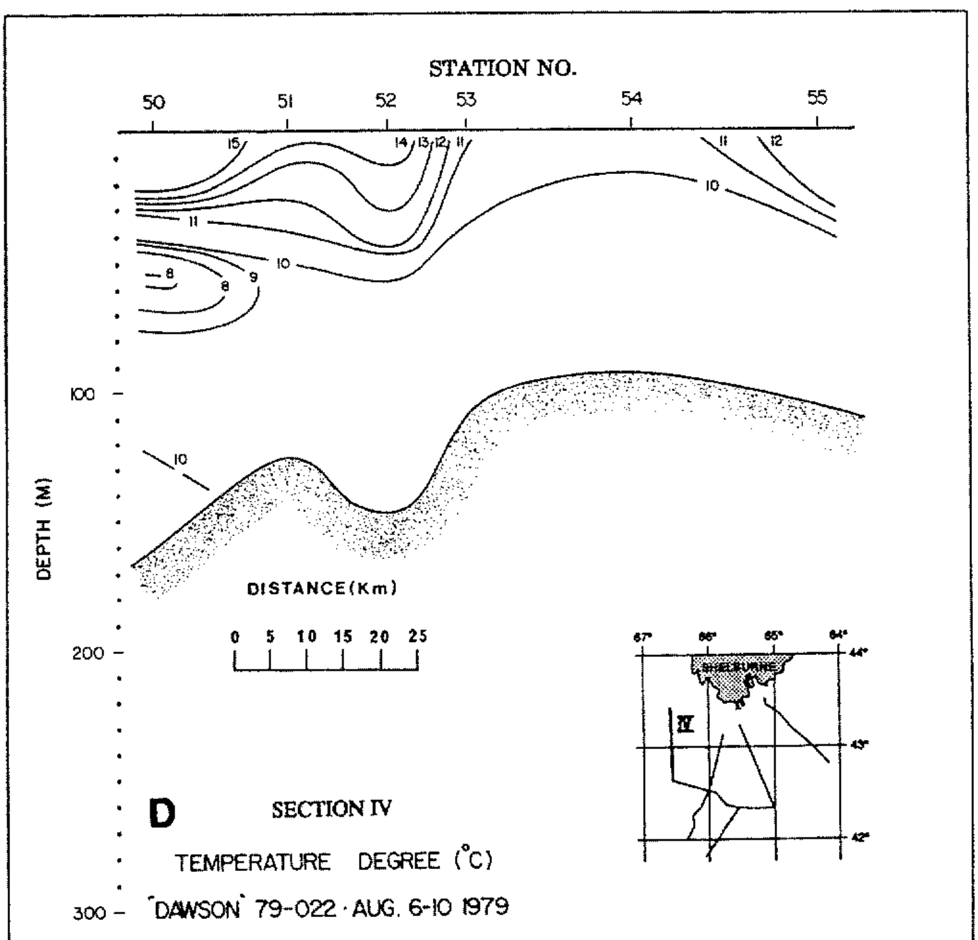


Figure 12a-d. Observed temperature variations along sections I-IV (A-D) off southwest Nova Scotia during August, 1979. (Tee et al., 1993).


STATION NUMBER
38 37 36 35 34 33 32 31 30 29 28 27 26 25 24 23 22 21
DEPTH (M)
0
100
200
300
DISTANCE (km)
SECTION III
TEMPERATURE (°C)
DAWSON 79-022 • AUG. 6-10 1979
C
SHELBURNE
III


STATION NO.
50 51 52 53 54 55
DEPTH (M)
100
200
300
DISTANCE(Km)
0 5 10 15 20 25
D
SECTION IV
TEMPERATURE DEGREE (°C)
"DAWSON" 79-022 · AUG. 6-10 1979
SHELBURNE
IV

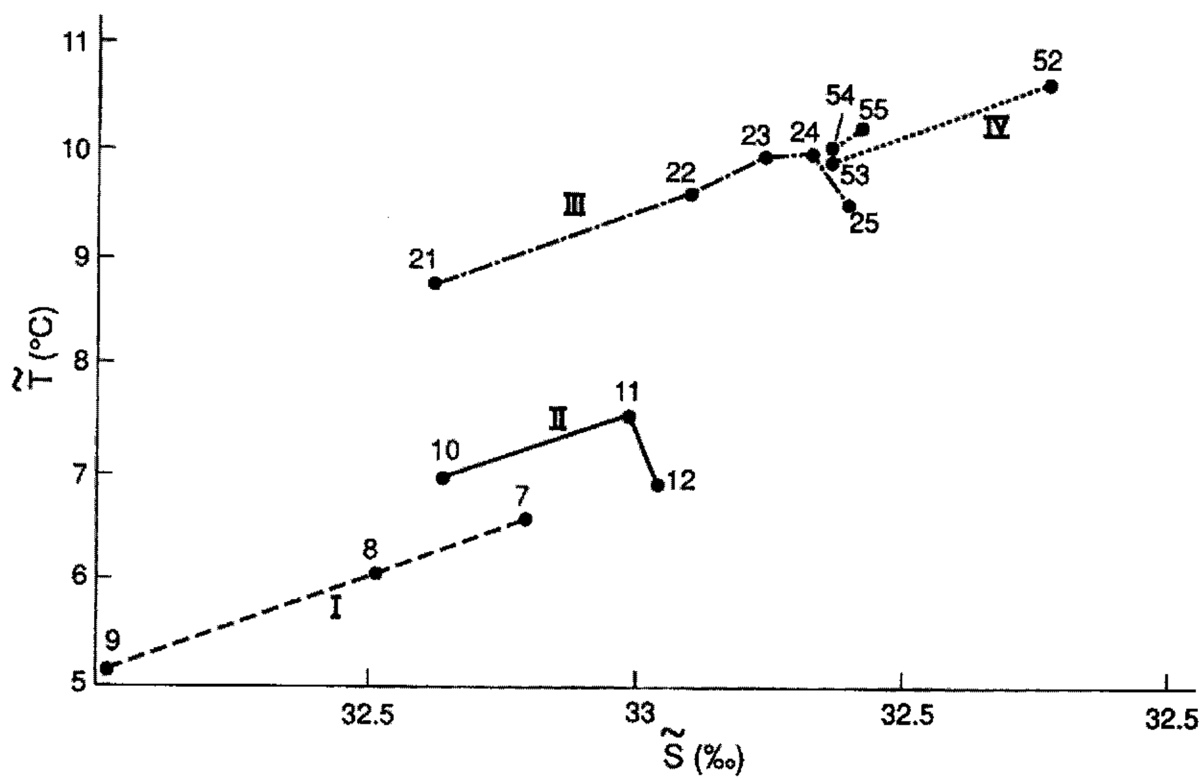


Figure 13. Depth-averaged temperature ($\tilde{T}$) and salinity ($\tilde{S}$) at selected hydrographic stations on Sections I (dashed), II (solid), III (dash-dot) and IV (dot) during August, 1979. (Tee et al., 1993).

west of Cape Sable could provide a source for the mixed water. Furthermore, a diagram of the depth-averaged temperatures and salinities of the inshore stations on Sections I to IV (Figure 13) suggests that the properties of the mixed water at Station 10 (7°, 32.65) are derived from combinations of those at Stations 7, 8, 11, and 12, i.e., from water which lies outside the 65m isobath and to the east of where the tidal mixing front occurs. The inshore waters at Station 9 (60m isobath on Section I) probably have little impact on the mixing zone because 1) the salinities and temperatures are too low, and 2) the along-shore transport inside the 60m isobath is estimated to be less than 20% of the onshore transport caused by the upwelling. Clearly, the nearshore stations west of Cape Sable (21-25, 52-55) have temperatures and salinities too high to contribute significantly to the mixed water properties.

Finally, the nitrate sections (Figure 14) demonstrate that topographic upwelling supplies nutrients to the upper layers of the mixing zone. The surface concentrations at Station 10 are high (~4 μM) and the depth-averaged concentration (6.3 μM) is very similar to those at Stations 7 (8.12μM), 8 (6.62μM), 11 (6.79μM), and 12 (9.24 μM). The close agreement of these values indicates that nitrate uptake rates are not significant and that the concentration may be treated as a conservative property. This is plausible since the nutrient-rich deep water is removed from the photic zone until mixed upward by the tide in shallow water, where its exposure is then limited by the mixing itself (Fournier, et al. 1984).

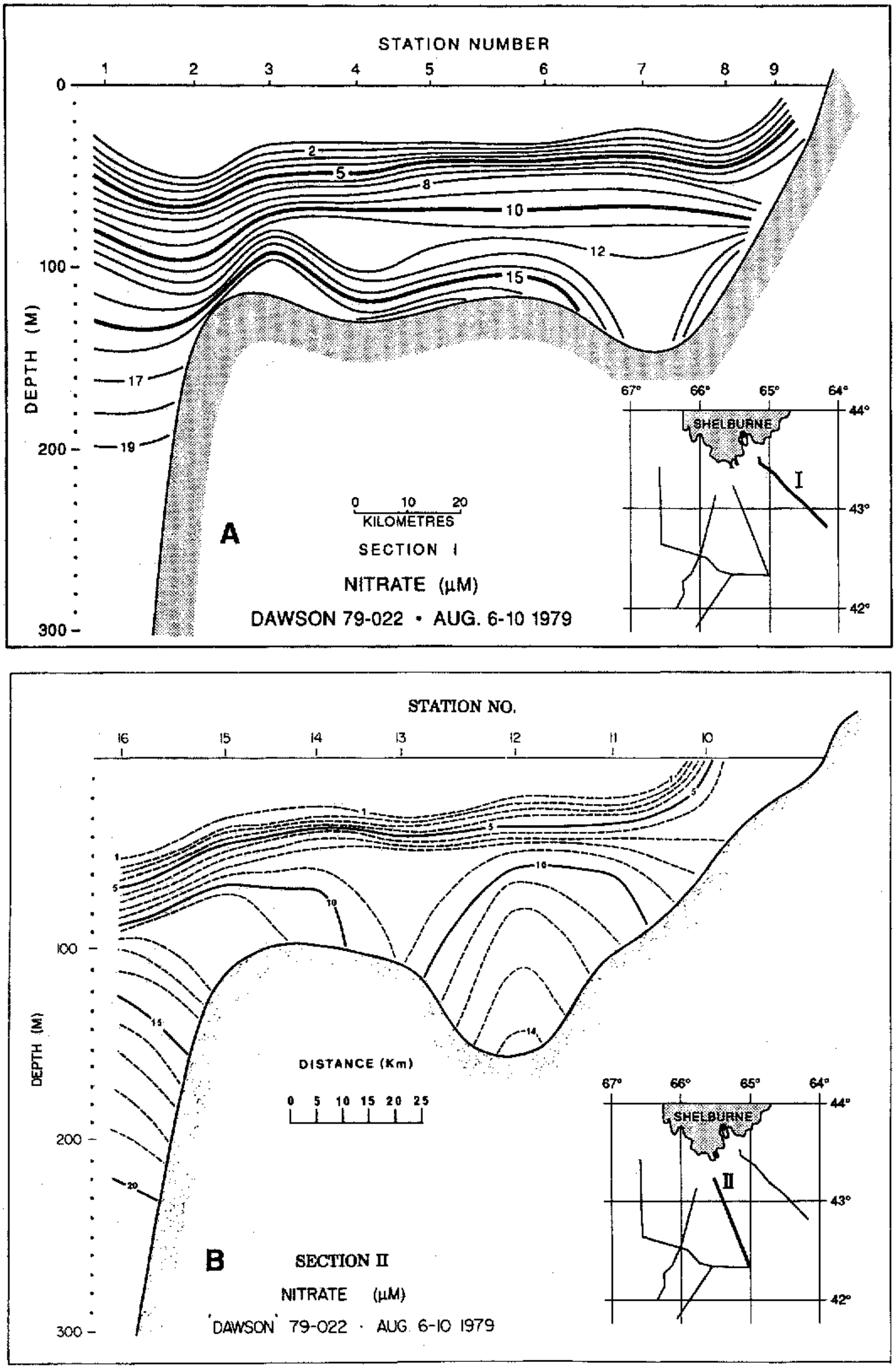


Figure 14. Nitrate concentrations on (A) section I and (B) section II during August, 1979. (Tee et al., 1993).

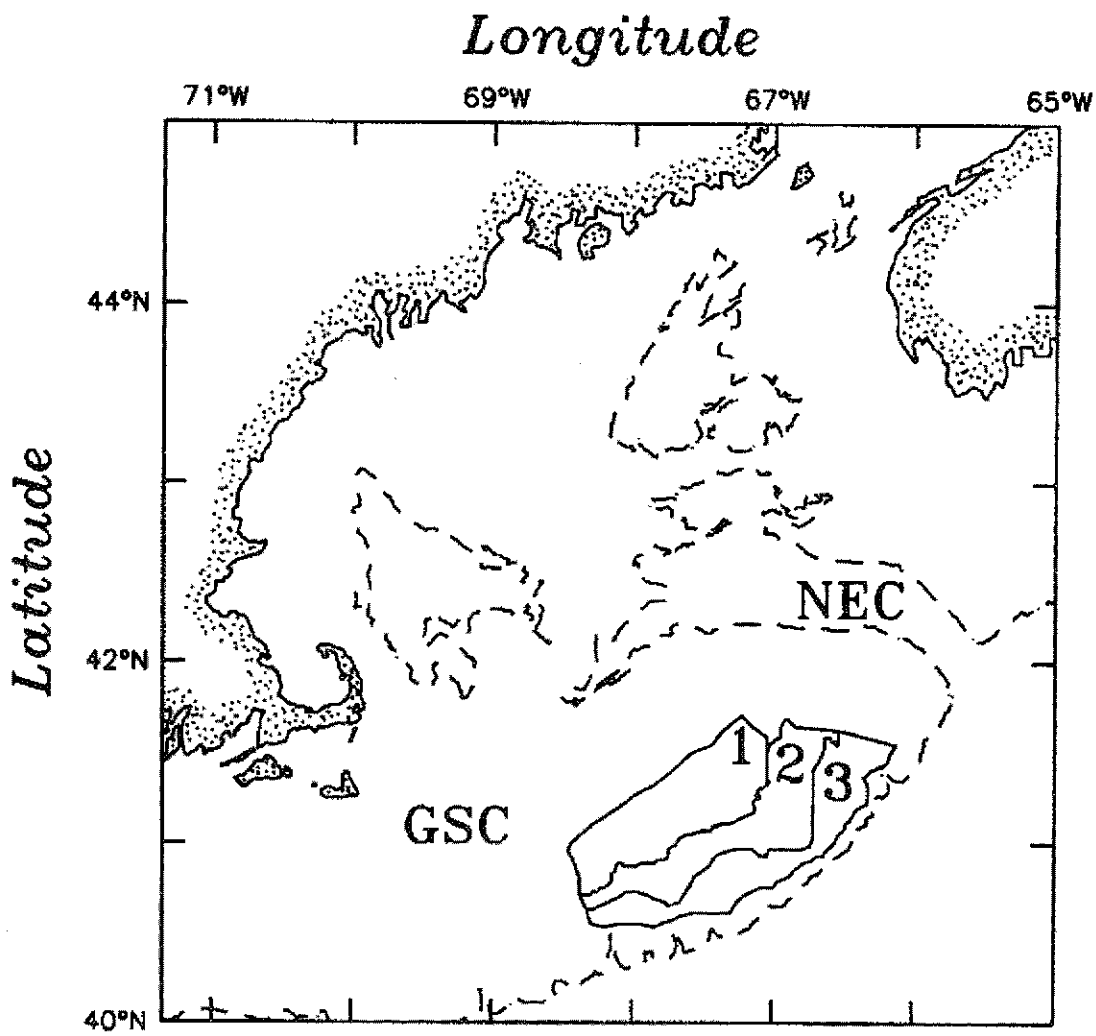
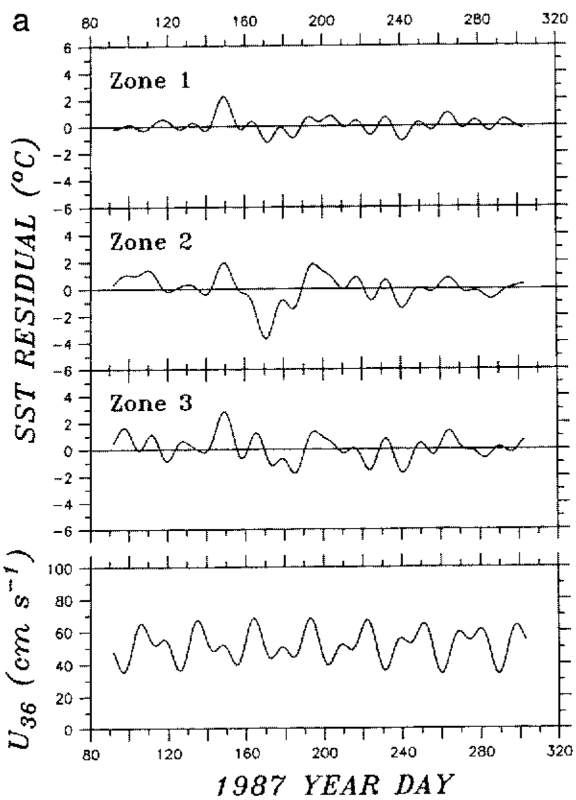


Figure 15. Locations of depth zones 1 (<60m), 2 (60-80m), and 3 (80-100m) on Georges Bank. (Bisagni and Sano, 1993).

Modulation of Tidal Mixing on the Southern Flank of Georges Bank

Accurate predictions of temporal variability of the properties and extent of tidal mixing zones and fronts due to monthly and fortnightly modulation of the tidal currents requires knowledge of the time-dependence and efficiency of turbulent mixing in a stratified current. Simpson and Bowers (1981), for instance, detected a spring-neap cycle in the movement of tidal fronts in the Irish and Celtic Seas, but found that to match those positions with the empirical criterion required the specification of a variable mixing efficiency. In the absence of such information for the Gulf of Maine, Loder and Greenberg (1986) ignored such effects in their approximate predictions (Figure 9b) based on constant efficiencies.

Recently, Bisagni and Sano (1993) have investigated the variability of sea surface temperature in three depth zones of the southern flank (<60m, 60-80m, 80-100m; Figure 15) using satellite Advanced Very High Resolution Radiometer (AVHRR) data from April-October, 1987. To remove the significant influences of meteorological forcing, they filtered the daily-average data to remove energy at 1-7 days but pass the 15- and 28-day spring-neap signals (Figure 16a). Cross-correlations between the SST signals and mid-depth tidal current magnitude over the latter "destratifying" portions



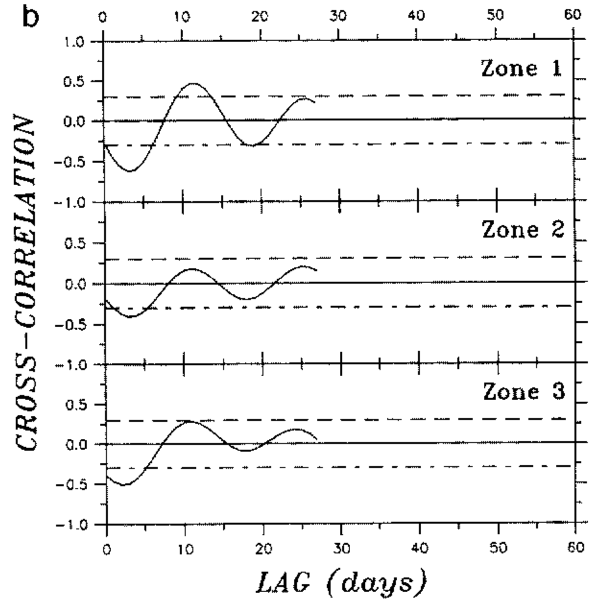


Figure 16. (a) Low-pass filtered SST residuals in zones 1-3 and daily-average tidal current magnitude at 36m during year days 92-303 (2 April-30 October) 1987. (b) Cross-correlation function of low-pass tidal current and low-pass SST residuals for year days 198-303, 1987. 95% confidence limits are also shown. (Bisagni and Sano, 1993).

of the records (Figure 16b) indicate significant negative correlations in all three zones, with SST lagging current by roughly 3 days. The extension of this relationship into zone 1 (<60m), where the water column is nearly homogeneous year-round(Bisagni, 1992), suggests lateral movement of cold, nutrient-rich subthermocline waters from zones 2 and 3 onto central Georges Bank during spring tides. In fact, lateral, cross-zone flow of order 1 cm s^{-1} has been measured during the stratified summer season immediately below the seasonal thermocline (Butman et al., 1987). Candidate forcing mechanisms for such flows include (1) tidal rectification, (2) friction-induced ageostrophic flows, (3) baroclinic eddies near the front, and (4) longshore pressure gradients. Maximum SST residuals were found in zone 2, in agreement with the mean position of the deep "cold pool" of exiting Maine Intermediate Water, which is centered on the 80 m isobath (Flagg, 1987).

Bisagni and Sano (1993) interpreted these observations in terms of a simple, one-dimensional mixing model with a time-dependent vertical eddy diffusivity, K_v (Loder and Garrett, 1978). Assuming that K_v varies as the square of the current magnitude, the predicted variation of SST over the spring neap cycle is 3.3°C with a 3-day lag behind the current, in close agreement with the observations.

The importance of the spring-neap cycle to phytoplankton and primary production on the southern flank lies both in the alternation of mixed and stable hydrodynamic states and the apparent on-bank transport of cold, nutrient-rich water from the "cold pool". Given the observed inverse correlation between temperature and nitrate correlation, it is expected that periods of negative SST residuals during spring tides also represent periods of enhanced vertical fluxes of nitrates. Alternating periods of near-surface enrichment (spring) and increased stability with sufficient light may lead to a series of blooms and sustained primary production on the Bank.

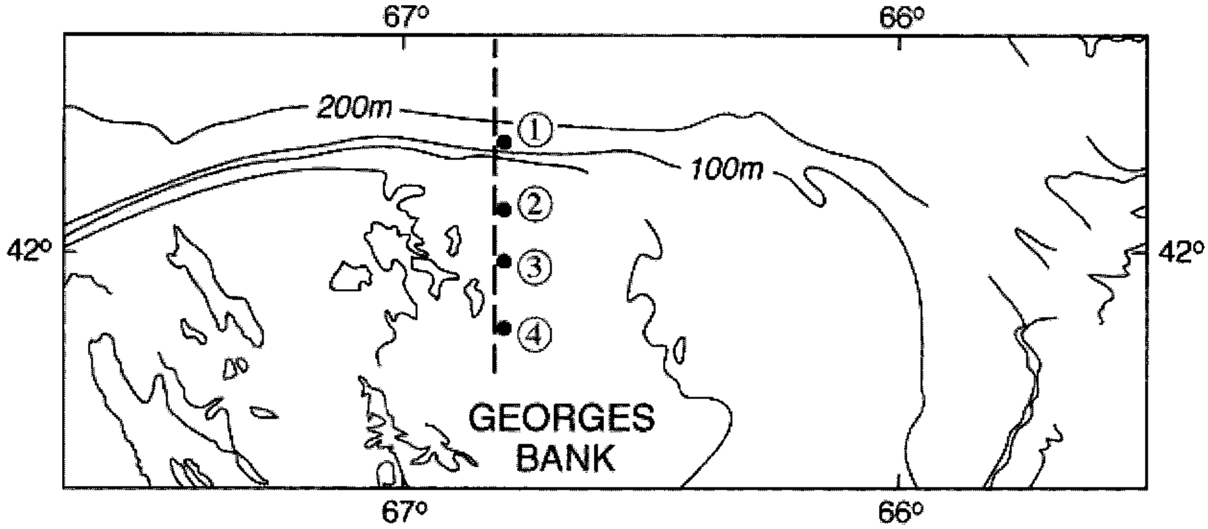


Figure 17. Location of principal study line (dashed) and mooring sites (solid dots) for Georges Bank Frontal Study, 1988-89. (Loder, et al., 1992, 1993).

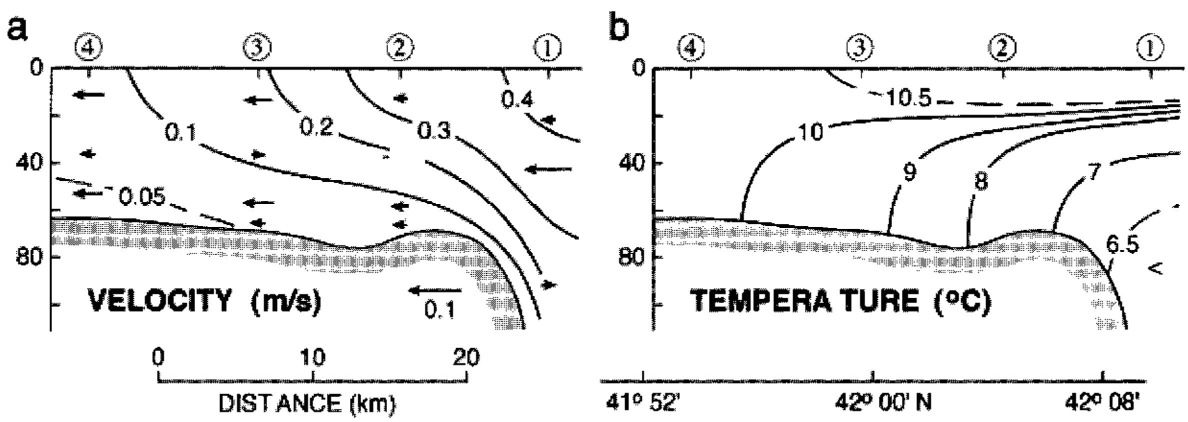


Figure 18. (a) Along-front (isotachs) and cross-front (vectors) mean currents, and (b) mean temperature from moored current meters on northern flank line during 2-4 July, 1988. (Loder et al., 1992, 1993).

Mixing Processes on the Northern Flank of Georges Bank

Perhaps the most detailed and comprehensive observations of tidal mixing and frontal processes in this region were collected during the Georges Bank Frontal Study, 1988-89 (Loder et al., 1992,1993). Measurements included time series from moored current meters and thermistor chains; repeated CTD, Batfish (towed, undulating CTD), nutrient, and acoustic doppler current profiler (ADCP) sections; several near-surface drifter deployments; and repeated drops of the free-fall turbulence profiler EDSONDE (Oakey, 1988) along the principal study line across the Northern Flank (Figure 17).

The moored measurements provide a reasonably smooth picture of the mean velocity and temperature fields over the flank (Figure 18). Here the currents have been resolved into a local "frontal" coordinate system, defined by the "skew eddy fluxes" of temperature (Loder and Horne, 1991), to reveal an approximation to the classical two-cell structure of the cross-frontal velocity, thought to be the primary cross-frontal exchange mechanism (Garrett and Loder, 1981). However, barotropic tidal advection (10-15 km excursions) and its interaction with variable topography and other waves causes considerable straining of the "instantaneous" hydrographic fields. Even more dramatic is the formation of intense groups of internal waves near the bank edge during each

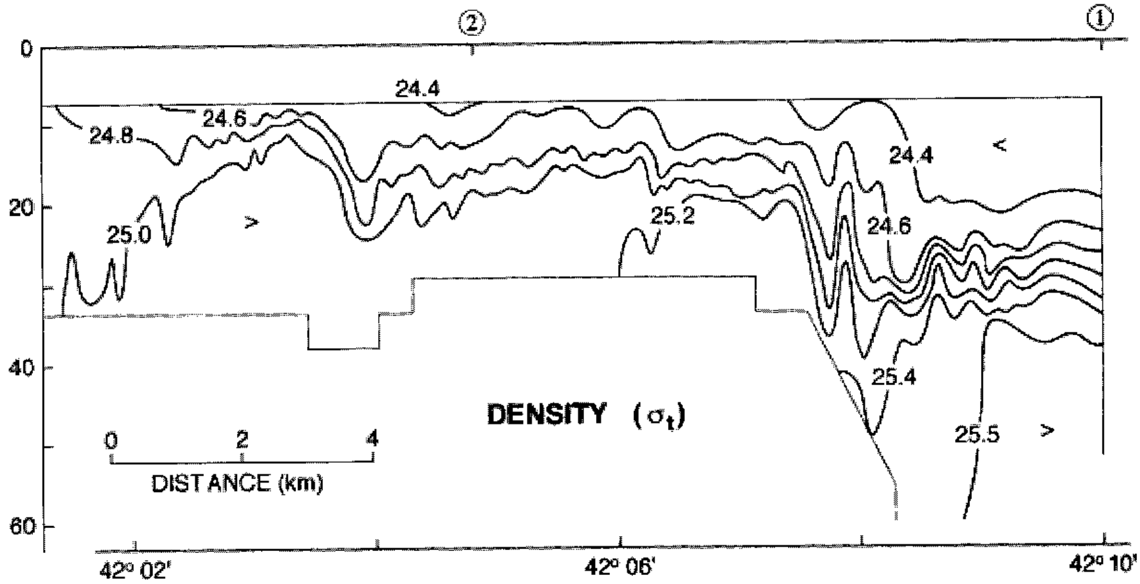


Figure 19. Density distribution from a Batfish section along the study line on the northern flank near the end of off-bank flow on 28 June 1988. Contours reveal tidal front region (far left), mature depression near site 2 approaching the front, and two newly-formed depressions over the slope near site 1. (Loder et al., 1992, 1993).

tidal cycle. In the early stages of off-bank flow, depressions are generated over the slope and begin to propagate away in both directions. However, the strength of the off-bank currents inhibits movement of the shoaling waves onto the bank (Froude number >1), resulting in the development of a pronounced internal hydraulic jump (≈30m), which is visible in Batfish density sections near the end of the off-bank flow (Figure 19). As the tide turns, this disturbance propagates onto the bank and evolves into two soliton-like features (Figure 19), which appear to dissipate in the vicinity of the tidal mixing front. The disturbances which propagate away into deeper water also appear to evolve into an energetic wave packets which have been viewed from space (e.g., LaViolette et al., 1990).

The hydraulic jump has great potential for vertical mixing at the bank edge during off-bank flow, while the propagating depressions provide a regular energy source for mixing in the frontal zone. In both cases, mixing should be concentrated in the pycnocline rather than at the bottom, as in barotropic tidal dissipation. Brickman and Loder (1993) have studied the energetics of propagating disturbances by (1) calculating the available potential energy in the residual density deviations found in nine repeated Batfish sections across the bank edge and (2) estimating the kinetic energy in the waves from both thermistor chain data and internal soliton theory. They find that the total energy in these 2 km long disturbances is approximately 35 Jm^{-3}, which represents a significant contribution to the potential energy requirements of the surface buoyancy inputs over the frontal mixing zone. Similarly, assuming a vertical nitrate contrast of 10 µM, the flux associated with internal wave dissipation would be sufficient to support the nitrate demand of the frontal zone (Horne et al., 1989; see Section 4 below). Using turbulent microstructure and nitrate profile measurements directly, Horne et al., (1996) have attempted to verify that the vertical nitrate flux in the frontal zone is sufficient to satisfy the biological requirements in the euphotic layer (i.e., within 40 m of the surface). Their estimates indicate that the tidal-average flux is less than (30-46%), but comparable to, the nitrate demand. Given the sparse sampling in time and space, these discrepancies are well within the bounds of experimental error.

Microstructure measurements during anchor stations at the four mooring sites (Figure 17) reveal the spatial and temporal variability of turbulent processes over the tidal cycle (Loder et al., 1993). The mean distributions of turbulent kinetic energy dissipation rate (ε) and small-scale temperature variance (χ_T) show the expected features (Figure 20): large values of ε near the

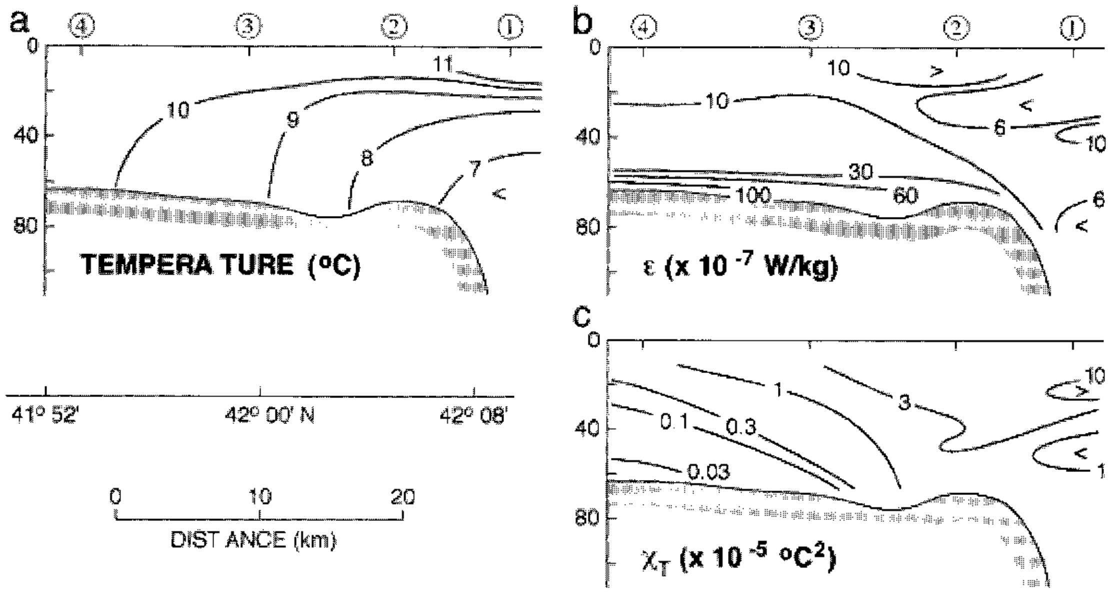


Figure 20. Cross-bank distributions of the mean value (over 92 microstructure stations) of (a) temperature, (b) TKE dissipation rate, ε, and (c) temperature variance, χ_T. (Loder et al., 1992, 1993).

sea floor and a general decrease toward the bank edge and increases of the χ_T towards the surface and bank edge. In addition there are local maxima in ε near the sea surface at the bank edge and at mid-depth over the slope. Sorting these data temporally (Figure 21a) and comparing with "macroscale" data reveals that the mid-depth maximum is associated with the internal hydraulic jump (Figure 19), while the surface maximum results from dissipation of large amplitude internal waves as the tide turns. The associated vertical diffusivities for heat indicate values generally in the range of 10-200 x $10^{-4} m^2 s^{-1}$ (Figure 21b). The corresponding average downward heat fluxes over the 10-34m depth interval range from 430 to 50 Wm^{-3} at moorings 1-4 respectively. These estimates bracket climatological surface input values.

The net result of this study (and associated biological program) is a new conceptual model for the northern Georges Bank Frontal System (Figure 22 — page 92), including a stratified tide-topography interaction at the bank edge which is coupled to the tidal mixing front via internal wave propagation and dissipation (Loder et al., 1992b). The physical regime features bottom intensified vertical mixing on the bank plateau and pycnocline mixing near the tidal front and at the bank edge. The associated biological regime shows a twin peak in new nitrate production (f-ratio; Harrison et al., 1990) and zooplankton concentration gradients at the front and bank edge (Perry, et al., 1993). Both direct and indirect estimates of nutrient fluxes are consistent with the observed demand by primary production in the surface layer.

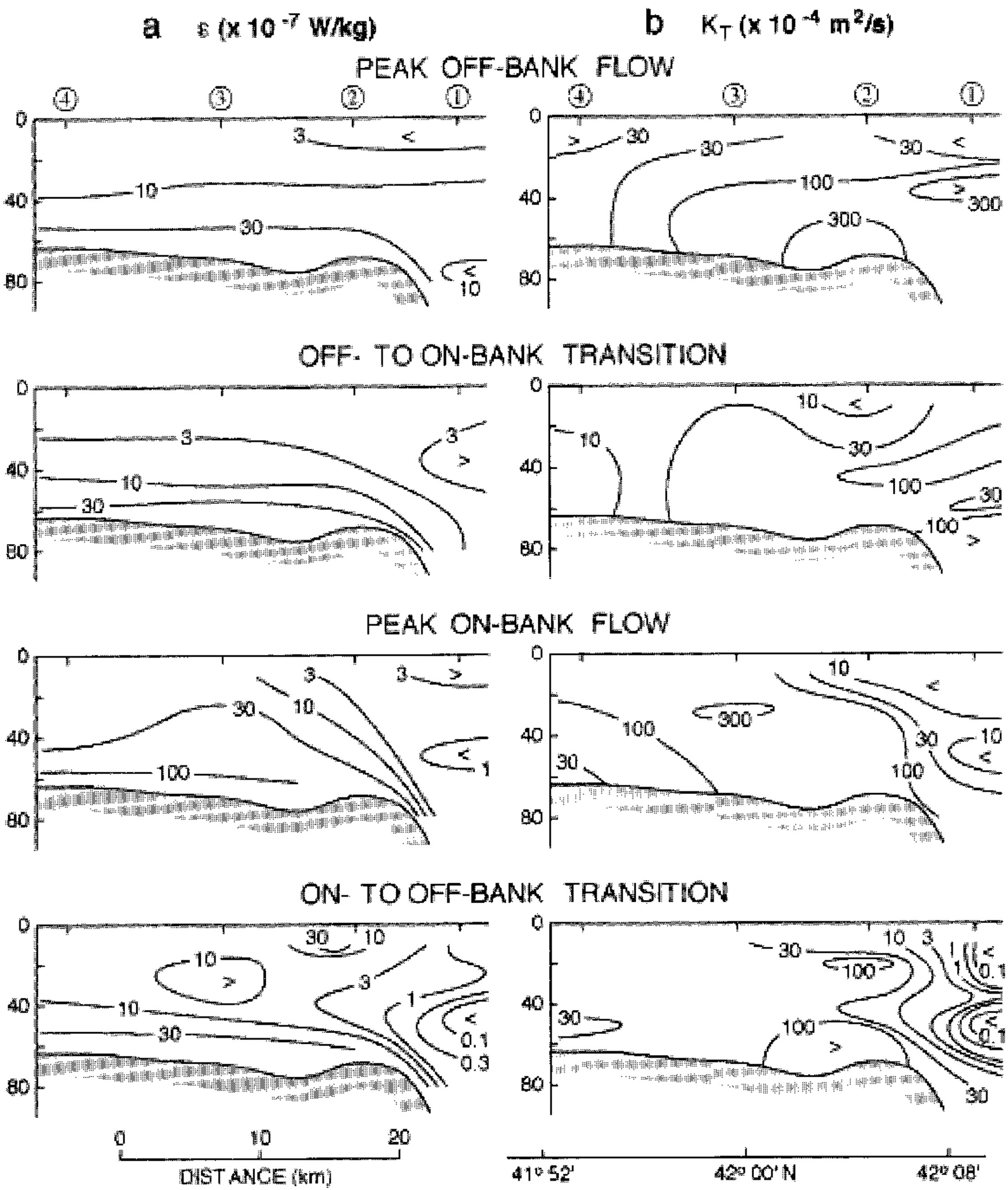


Figure 21. Temporal evolution over a tidal period of the cross-bank distributions of (a) TKE dissipation rate, ε ($/10^{-7}$ W kg^{-1}), and (b) vertical eddy heat diffusivity, κ_T ($/10^{-4}$ m^{2}s^{-1}) computed from microstructure stations. Microstructure stations have been sorted into four tidal phases based on the vertically-averaged cross-bank current at site 3. (Loder et al., 1992, 1993).

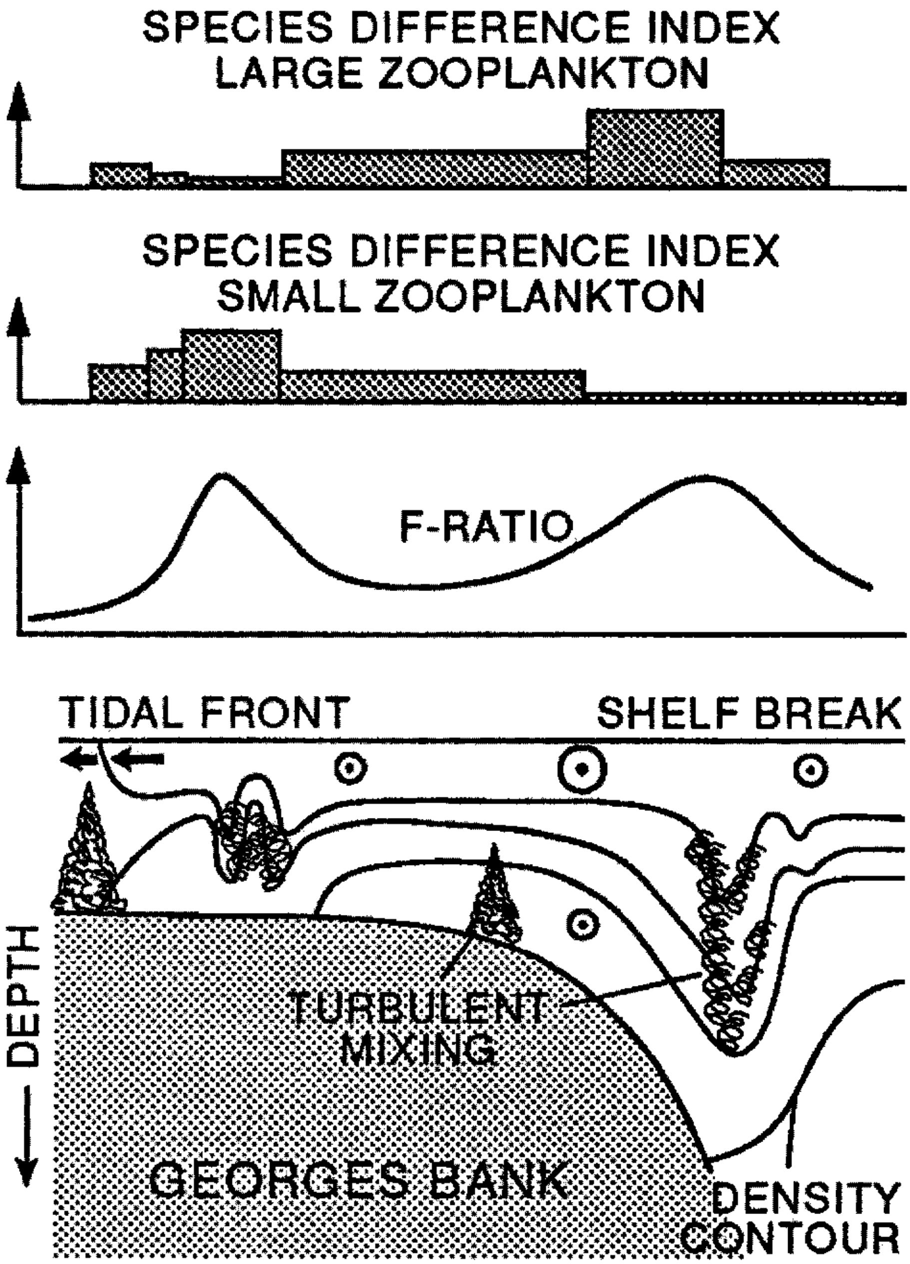


Figure 22. Summary of physical and biological regimes on northern Georges Bank in summer. The physical regime includes large tidal currents and excursions, a tidal front with surface convergence, along-bank current jet centered on the slope, internal waves and intense small scale turbulence. The f-ratio ("new"/total production) peaks at both the tidal front and bank edge, and the zooplankton show similar tendencies for small and large animals, respectively. (Loder et al., 1992b).

Figure 23. Satellite infrared SST image for 25 July 1984. (Petrie et al., 1987)

Wind-driven Upwelling

Bigelow (1927) and Hachey (1935) were the first to have reported the occurrence of cool summertime surface temperatures in response to southwesterly winds along the coasts of Nova Scotia and the Gulf of Maine. More recently, there have been passing references to these effects in the Gulf (e.g., Brooks and Townsend, 1989), but the upwelling process and subsequent frontal development has been most clearly identified on the Scotian Shelf by Petrie et al. (1987). They present a varied set of remote and *in situ* observations of sustained upwelling in response to persistent (27 June-27 July), favorable longshore winds during the summer of 1984. Toward the end of this period, a wide band of cool (4-7°C) surface waters had developed along the Nova Scotian coastline and the boundary between the upwelled and warmer offshore waters had deformed in to a series of cold plumes extending up to 175 km from the coast, with longshore spacings of 50-75 km (Figure 23). A simple two-layer model of the process provided a reasonable interpretation of the satellite and coincident coastal and offshore hydrographic data in terms of the source, maintenance and extent of the cold surface water, but adjusted sea level observations at Halifax were not well matched. As for the plume structure, results from a set of idealized three-layer models suggested that the primary mechanism for generating the plumes was baroclinic instability of the front itself. Predicted wavelengths (50-80 km), propagation speeds, and growth time scales (2-4 days) were all consistent with the observations.

The rate of upwelling during this period was approximately $2x10^{-5}$ m s^{-1}, or 20 m every 10 days. Over a coastal strip of 10 km width and 500 km length, this implies a vertical transport of 10^5 m^3s^{-1}, comparable to the average summer longshore transport ($2x10^5$ m^3s^{-1}, Drinkwater et al., 1979). Furthermore, Fournier et al. (1977) have estimated the spring/summer nitrogen demand on the Scotian Shelf at 1.6 mmol N s^{-1} per meter of coastline. Assuming the average nutrient concentration in the cold intermediate layers is of order 10^{-2} mM, the observed upwelling rate supplies 1.0 mmol N s^{-1} per meter, close to the estimated demand. Thus it appears that summer coastal upwelling could supply a significant nutrient flux to the surface layers on an intermittent basis.

Petrie (1983) has also shown that significant upwelling from depths up to 400 m occurs at the Scotian Shelf break (~ 200 m isobath) in response to longshore winds of two or more days duration. This response, primarily to fall and winter storms, appears to be confined to within roughly 10 km of the shelf break and to be "channeled" by local topographic variations on the shelf. The zone between 200 and 400 m depth at the shelf edge is also a rich source of nutrients (Smith, 1978), so the wind-driven upwelling may also be partly responsible for the exceptionally high productivity there (Fournier et al., 1977).

Recent Model Results

Recent numerical model developments related to circulation and mixing in the Gulf of Maine may be placed into two general categories: process models and comprehensive models. The former are idealized to study a particular process or mechanism, usually over a limited domain, while the latter attempt to simulate most of the relevant physical processes in the system in order to capture, to a degree, the complexity of the real case. While the boundary between these two types of models is arbitrary, since all models are idealized to some extent, the distinction is useful. Lynch, et al. (1996) (whose prognostic finite element model is a prime example) define the attributes of comprehensive coastal circulation models as providing (1) shelf-scale geographic coverage, (2) adequate local resolution of topography, coastlines and flow fields, and (3) internal physics sufficient to simulate all important processes in tidal time. This will serve as a working definition.

Process Models

As described above, Tee, et al. (1993) used a weakly nonlinear, limited-area tidal model to study and interpret the topographic upwelling process off Cape Sable, Nova Scotia. The fluid was assumed to have uniform density, and lateral boundary conditions were derived from Greenberg's (1983) depth-averaged model for the Gulf and Bay of Fundy in order to simulate the system response near M_2 properly. The equations were discretized on a 7x7 km rectangular grid with 41 vertical levels (concentrated near the bottom), and both the vertical eddy viscosity and bottom friction coefficient were specified from empirical data. The success of the model in matching the observations indicates that topographic upwelling is driven primarily by tidal rectification, supplemented by intense tidal mixing off Cape Sable. The model prediction of weak vertical shear in the tidal residual currents is consistent both with observations (Tee, et al., 1987) and with the mechanism for producing upwelling by cross-isobath residual transport. The model also provides realistic time scales for horizontal advection to compare with vertical mixing rates, even though the latter are not included explicitly in the model.

In a similar vein, Greenberg et al. (1997) have recently examined the wind-driven circulation in the Gulf of Maine and on the Scotian Shelf at frequencies down to the "storm band" (2-5 d periods) using a 3-D, barotropic, finite-element model with spatially-varying eddy viscosity and bottom friction coefficients. The uniform atmospheric forcing and the solutions are harmonic in time, and the dynamics are linear, although the spatial variations in friction are derived from a nonlinear M_2 tidal solution. Their results suggest that the barotropic response is rather insensitive to forcing frequency, such that the "storm band" solutions resemble the quasi-steady (20 d period) response, with some notable exceptions on the outer shelf. Furthermore, as noted by others (e.g., Schwing, 1992a, 1992b), the complete solution to the

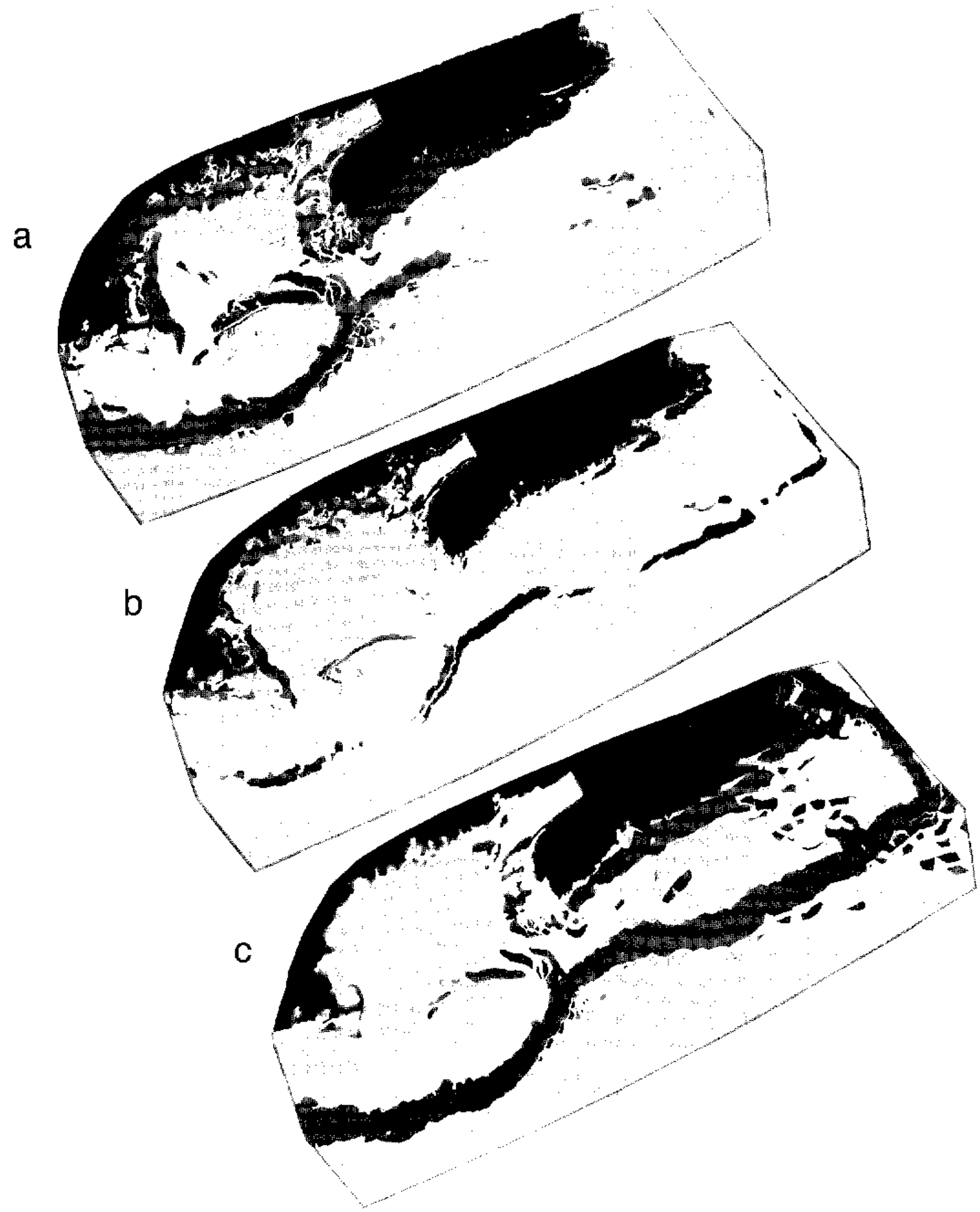


Figure 24. Distributions of bottom vertical velocity in low-frequency model solutions for (a) along-shore (northeastward) wind stress, (b) cross-shelf (southeastward) wind stress and (c) no stress but a 0.1 m coastal setdown at the northeastward coastal boundary. Major areas of upwelling lie along the coast and shelf break (dark bands) for the along-shelf stress and boundary set-down cases; the response to cross-shelf stress is primarily downwelling at the shelf break and along the eastern edges of Massachusetts and Cape Breton (also dark bands in the absence of color). (Greenberg et al., 1997)

dominant alongshore wind stress consists of both locally- and remotely-forced components. Greenberg et al. (1997) simulate the latter as a sea-level setup on the northeastern boundary of the domain. Thus the various components of the wind-driven pressure field, along with surface and bottom Ekman layer divergences, produce wide-spread areas of up- and downwelling in areas of strong current and bottom slopes (Figure 24). These results may be reasonable simulations of the forcing functions for observed coastal and shelf break upwelling, but they

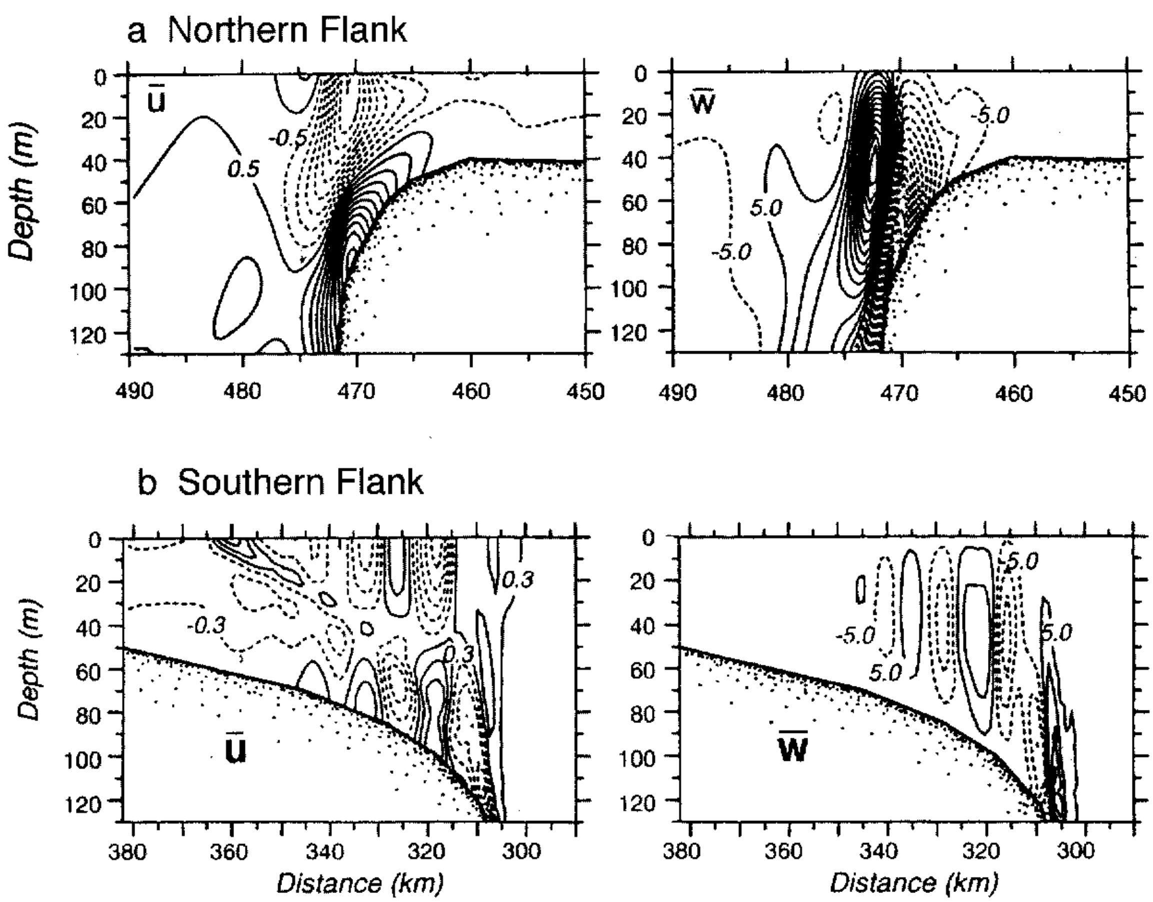


Figure 25. Structures of tidal-average cross-bank circulation for 2-D model solutions on the (a) northern and (b) southern flanks (Chen et al., 1995).

do not capture the baroclinic nature of the observed responses (e.g., Figure 23). Furthermore, the sensitivity of the model solutions to the strength of bottom friction and spatial variations in the background vertical mixing requires a more sophisticated treatment of turbulence.

Chen and Beardsley (1995) and Chen et al., (1995) have used a two-dimensional implementation of a Boussinesq, hydrostatic, nonlinear model with Mellor and Yamada (1982) turbulence closure to study the complex process of stratified tidal rectification on Georges Bank. Starting from a state of uniform thermal stratification representing summer conditions, their model develops tidal fronts at the 40 and 60 m isobaths on the northern and southern flanks, respectively, similar to their observed locations. The structure of the summer tidal-average Eulerian residual cross-bank current shows a single strong circulation cell on the northern flank (Figure 25a) and a multiple-cell structure on the southern flank (Figure 25b). The northern flank cell does not resemble the Loder et al., (1992) cross-frontal structure deduced from moored measurements (Figure 18), but the observed structure may be highly underresolved and/or sensitive to local topography and stratification. A diagnosis of the model dynamical balances suggests that stratification contributes significantly to both along-bank and cross-bank residual currents through complex nonlinear interactions among barotropic and internal tidal currents, and also through its influence on vertical mixing and friction.

A final example of process modeling is Lamb's (1994) simulation of internal wave generation over the northern flank of Georges Bank. This model is 2-D, fully-nonlinear, frictionless, and baroclinic. Using background fields and forcings derived from Loder et al.

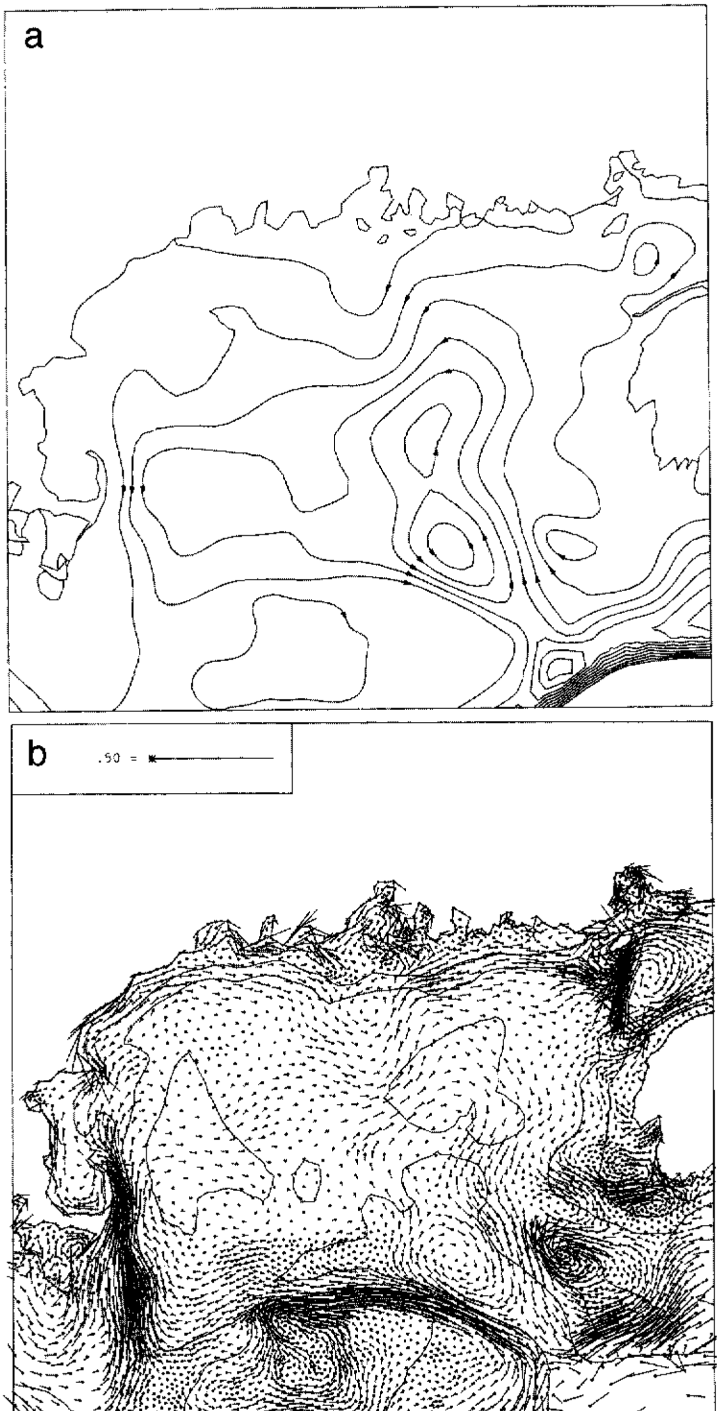


Figure 26. Comprehensive model solution (Lynch, et al., 1996) for Gulf-wide, tidal-average solution for March-April. (a) Streamfunction, contour interval 0.1 Sv; and (b) vertical-average velocity (meters/second).

(1992) observations, Lamb successfully reproduced such features as the hydraulic jump over the bank edge, significant overturning above the slope, and the two on-bank propagating depressions every tidal cycle. His solutions also show a dispersive undular bore propagating away from the bank with energy content similar to the shoaling waves. However, the results are found to be very sensitive to a number of factors, including topography, background stratification, and tidal strength. These findings, in addition to the omission of friction, turbulent mixing and its influence on the background density field preclude a more detailed comparison of the model and observations.

Comprehensive Models

The Lynch et al., (1996) model is dynamically similar to that of Chen and Beardsley (1995a), but is implemented on a 3-D finite element grid covering the entire Gulf of Maine (except the upper Bay of Fundy) and the Scotian Shelf. Turbulent mixing is included through advanced turbulence closure (Mellor and Yamada, 1982) with various improvements (e.g., Galperin et al., 1988). The prognostic calculations of the seasonal circulation fields are initialized by earlier diagnostic calculations (Naimie, et al., 1994) that used climatological mean densities (winter: March-April; summer: July-August), forced by climatological mean wind stresses at the surface, and nudged toward the climatological surface density fields as the integration proceeds in tidal time. After spinup, the solutions are averaged over a tidal cycle to produce seasonal composite solutions. The summer depth-averaged current and transport streamfunction (Figure 26) reveal familiar features of the circulation, including clockwise gyres over Browns and Georges Banks, the cross-isobath flow responsible for topographic upwelling off Cape Sable, large-scale cyclonic gyres over Georges

Basin and the inner Gulf, and the Maine coastal current. A closer examination of the velocity transect on the northern flank of Georges (Figure 27) shows a two-cell cross-bank structure, which is significantly different from that of Chen et al. (1995), but nevertheless features strong upwelling over the slope region. Naimie (1996) has examined the prognostic seasonal solutions for Georges Bank and found improved levels of agreement with observations, particularly in summer, compared to earlier diagnostic results (Naimie et al., 1994). Lynch et al. (1996) also present realistic simulations of wind-driven mixed-layer development over Wilkinson Basin, for both summer and winter cases, suggesting the possibility of modeling processes associated with preconditioning and winter overturning in the western Gulf. Thus the comprehensive finite-element model appears to provide a means to explore all the dominant vertical transport processes in the Gulf of Maine in a realistic context.

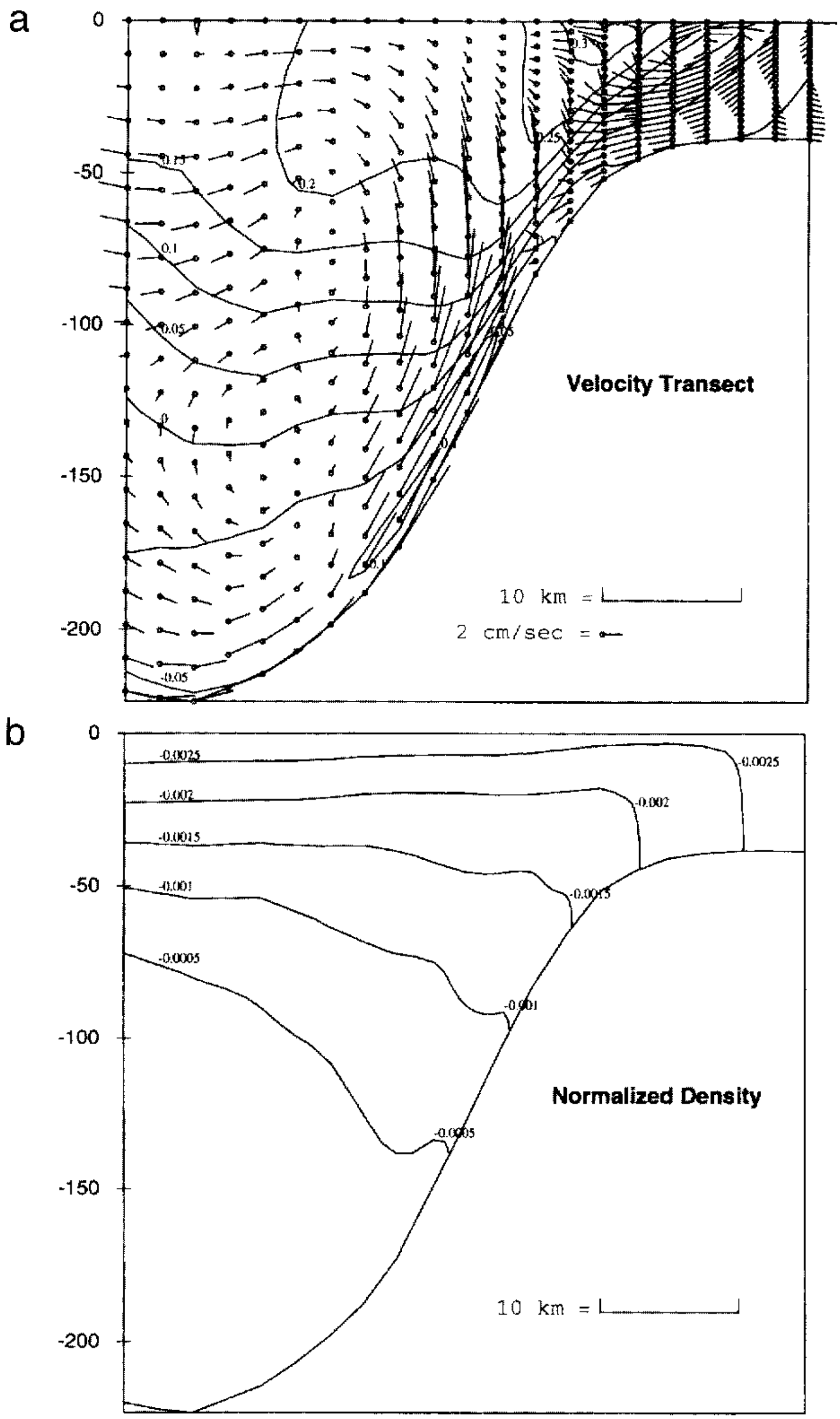


Figure 27. Tidal-average transect across the northern flank from the comprehensive model (Lynch, et al., 1996) for a stratified (summer) case showing: (a) along-bank current speed (isotachs) and cross-bank velocity (vectors); and (b) density anomaly, $(\rho - \rho_0)/\rho_0$.

Biological Significance

Early nitrogen budgets for the Gulf of Maine and Georges Bank (e.g., Schlitz and Cohen, 1984) suggest that 50% of the nitrogen demand arising from primary production is accounted for by regeneration within the system, but that 30% of "new" production, requiring physical transport of nutrients to the euphotic zone, is necessary to keep the system in balance. In attempting to quantify the nutrient supply rates, most of the physical process studies described in Section 2 have produced vertical nitrate flux estimates to the surface layers based crudely on mass flux, the amount of energy available for mixing, or microstructure measurements (e.g., Petrie et al., 1987; Tee et al., 1993; Brickman and Loder, 1993; Horne et al., 1996). The most detailed studies of primary and secondary productivity for this region have been conducted in connection with physical studies on the northern flank of Georges Bank (Loder et al., 1992). The stimulus of this work is the set of results from a 1985 hydrographic/nutrient survey of the northeast portion of the bank (Horne, et al., 1989) which included estimates of nitrogen and carbon uptake in samples from the central bank, frontal zone and the bank edge, based on isotope tracer experiments. Horne et al. (1989) found that f-ratios ("new"/total production) ranged from 0.23-0.31 in the well-mixed water and peaked near 0.70 at both the front and the bank edge. They also estimated that the cross-frontal flux of nitrogen exceeds the demand in both the frontal and well-mixed zones, suggesting that the phytoplankton are nutrient replete on the bank. However, as described earlier, the direct estimates of vertical nitrate flux from concurrent microstructure measurements (Horne et al., 1996) are insufficient to meet the demand in the frontal zone, though they are the right order of magnitude. Thus the observations are somewhat inconclusive regarding the nutrient supply rate on the northern flank.

Recently Chen and Franks (1996) and Franks and Chen (1996) have coupled a biological nutrient-phytoplankton-zooplankton (NPZ) model to the 2-D physical process model of Chen et al. (1995) in order to study the lowest trophic levels of the dynamic ecosystem on the northern flank. Using summertime initialization and M_2 forcing, they found that the biological fields, like the physical fields, were homogenized over the center of the bank and that the biomasses and fluxes agreed well with those of Horne et al. (1989). Phytoplankton were nutrient replete in the well-mixed area, exhibiting f-ratios of 0.30 while the horizontal nitrogen flux from the frontal zone would support twice that. Most importantly, phytoplankton patches found at the tidal front were supported by nutrient fluxes from the slope of the bank, below the euphotic zone. These upslope fluxes, occurring on both the northern and southern flanks were said to be caused by Lagrangian residual advection (Figure 28 — next page) associated with temporal variation in the sloping bottom boundary layer and the reflection of internal waves. However, Loder et al. (1997) describe similar behavior in their barotropic 3-D model, so barotropic tidal rectification may also contribute. In the 2-D stratified model, major bursts of vertical mixing were confined (both temporally and spatially) to a region just onbank from the front during full flood and within the front during flood-to-ebb transition. The NPZ results also indicate that the strength of the physical forcing is sufficient to cause local decoupling of trophic interactions. Thus decreases in the average zooplankton concentrations caused by vertical mixing allow phytoplankton growth on the bank and in patches at the front. At the same time, the mixing serves to pump nutrients into the euphotic zone to further stimulate growth and new production.

The Lynch et al. (1996) and Naimie (1996) comprehensive 3-D model has also been used to explore important biological questions, such as the seasonal supply routes for zooplankton *(Calanus finmarchicus)* from the Gulf of Maine to Georges Bank (Hannah et al., 1997). These results suggest that the primary upper-ocean supply mechanism is associated with surface Ekman drift in winter and early spring caused by the prevailing northwesterly mean wind stress. The convergence of this drift over Georges Bank, due to intense vertical mixing, may result in an accumulation of animals on the bank. Supply routes also depend on the large-scale gyres extant in the Gulf and its major basins (Figure 26) to transport deeper zooplankton to the northern flank jet where persistent upwelling between the 100- and 200-m isobaths is capable of injecting them into the surface Ekman layer. Hannah et al., (1997) conclude, however, that some behavioral component of the zooplankton motion is required to counteract the downward turbulent mixing associated with seasonal surface forcing. Nevertheless, model predictions that supply rates are highest in winter/early spring and lowest in summer are consistent with observations of seasonal abundance (Meise and O'Reilly, 1996). More accurate simulations of these processes requires the specification of a more realistic surface forcing for the model.

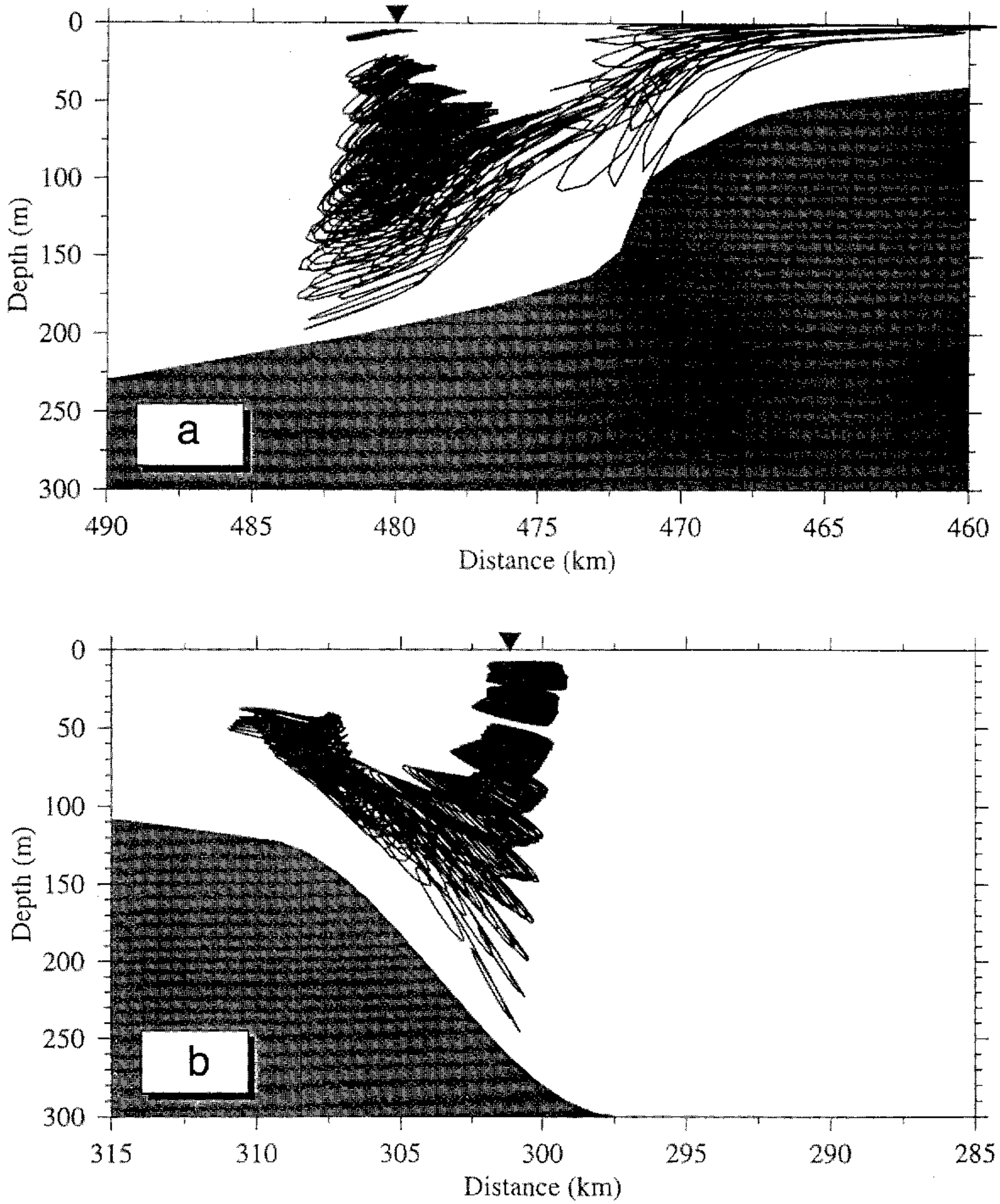


Figure 28. Model trajectories of particles released on the (a) northern and (b) southern flanks of Georges Bank. Filled triangle indicates the cross-bank location of the releases. (Chen and Franks, 1996).

Conclusions and Future Challenges

Over the past decade, field studies and numerical model developments have provided new insights into the dominant vertical mixing and transport processes driven by tides, wind and buoyancy fluxes in the Gulf of Maine and adjacent shelves. In particular, the mechanisms of winter overturning in the western Gulf, tidal mixing and stratified tidal rectification on Georges Bank and off southwest Nova Scotia, and wind-driven coastal upwelling have been explored and interpreted. Other potentially important processes not covered by the present review include (1) coastal current entrainment and interaction with wind-driven upwelling and (2) warm core ring interaction with coastal waters at the shelf edge.

On the modeling front, significant progress has been made in understanding the complex interactions associated with stratified tidal rectification on the northern and southern flanks of Georges Bank and in defining the climatological seasonal cycle in the 3-D circulation field. Moreover, the models have been used to address key biological issues, such as the physical basis for "new" production in the Georges Bank and southwest Nova Scotian ecosystems and advective pathways for both passive and active marine organisms. Questions regarding pathways and supply routes as well as large-scale trophodynamic modeling studies (e.g., Werner, et al., 1996) generally require 3-D comprehensive models to produce realistic simulations and to study important sensitivities of the results.

The most important challenge for the future of this research in the Gulf of Maine (and elsewhere) is the continued and increased exploitation of a blended approach using both field observations and numerical models. This approach is required for two reasons:

1. The intense variability of the actual 3-D circulation and the ecosystems it supports are invariably under-resolved by field measurements, even with today's sophisticated survey tools and remote sensing techniques. Model simulations help to identify key sites for observations and serve to integrate the field measurements.
2. Even comprehensive models are inadequate to simulate all relevant physical and biological process at all scales. Field observations will always be necessary for validation and identification of unmodelled factors.

In this scheme there are important roles for both process models to improve our understanding of particular mechanisms and for comprehensive models to provide realistic simulations and predictions. The full power of the comprehensive models has yet to be tapped. At present, there has been some progress on seasonal solutions for defining the climatological annual cycle, but important questions surrounding climate change research require simulations of interannual variability. At higher frequencies, it is also necessary to model storm response and shelf/slope water interactions and to validate the results with field observations. In these areas, newly developed data assimilation techniques will be useful.

In the area of vertical transport and mixing, the important topics for future model-based research include both wind- and tidally-driven processes. A key region to study storm response with the comprehensive 3-D model is in the vicinity of the winter overturning phenomenon in Wilkinson Basin. After validation with measurements, the model could be used to simulate observed interannual changes in the supply of Maine Intermediate Water associated with variations of wind and buoyancy forcing. Ultimately, climate change scenarios could be addressed.

Also, following the successes of process models for Georges Bank and southwest Nova Scotia, 3-D biological/physical modeling should be pursued in both regions and at the other tidal mixing "hot spot" near the mouth of the Bay of Fundy. Results should provide valuable insights into these richly productive ecosystems.

Acknowledgments

The author is indebted to Dr. J. W. Loder for his critical review of this manuscript. He also thanks Dr. W. G. Harrison for useful discussions of the biological questions.

References

Bigelow, H. B. 1927. Physical oceanography of the Gulf of Maine. *Bull. U.S. Bur. Fish.*, 40 :511-1027.

Bisagni, J. J. 1992. Differences in the annual stratification cycle over short spatial scales on southern Georges Bank. *Cont. Shelf Res.*, 12:415-435.

Bisagni, J. J. and M. H. Sano. 1993. Satellite observations of sea surface temperature variability on southern Georges Bank. *Cont. Shelf Res.*, 13:1045-1064.

Brickman, D. and J. W. Loder. 1993. Energetics of the internal tide on northern Georges Bank. *J. Phys. Oceanogr.*, 23:409-424.

Brooks, D. A. and D. W. Townsend. 1989. Variability of the coastal current and nutrient pathways in the eastern Gulf of Maine. *J. Mar. Res.*, 47:303-321.

Brown, W. S. and R. C. Beardsley. 1978. Winter circulation in the western Gulf of Maine. Part 1: Cooling and water mass formation. *J. Phys. Oceanogr.*, 8:265-277.

Brown, W. S. and J. D. Irish. 1993. The annual variation of water mass structure in the Gulf of Maine: 1986-1987. *J. Mar. Res.*, 51:53-107.

Butman, B., J. W. Loder, and R. C. Beardsley. 1987. The seasonal mean circulation: Observation and theory. In *Georges Bank*, ed. R. M. Backus, 125-139. Cambridge: MIT Press.

Chen, C. and R. C. Beardsley. 1995. A numerical study of stratified tidal rectification over finite-amplitude banks. Part I: Symmetric banks. *J. Phys. Oceanogr.*, 25:2090-2110.

Chen, C., R. C. Beardsley, and R. Limeburner. 1995. A numerical study of stratified tidal rectification over finite-amplitude banks. Part II: Georges Bank. *J. Phys. Oceanogr.*, 25:2111-2128.

Chen, C. and P. J. S. Franks. 1996. A coupled physical-biological model of Georges Bank. unpublished manuscript.

Clarke, R. A. and J-C. Gascard. 1983. The formation of Labrador Sea Water. Part I: Large-scale processes. *J. Phys. Oceanogr.*, 13:1764-1778.

Drinkwater, K., B. Petrie, and W. H. Sutcliffe. 1979. Seasonal geostrophic transports along the Scotian Shelf. *Estuarine Coastal Mar. Sci.*, 9:17-27.

Flagg, C. N. 1987. Hydrographic structure and variability. In *Georges Bank*, ed. R. M.. Backus, 108-124. Cambridge: MIT Press.

Fournier, R. O., J. Marra, R. Bohrer, and M. Van Dat. 1977. Plankton dynamics and nutrient enrichment of the Scotian Shelf. *J. Fish. Res. Board Can.*, 34:1004-1018.

Fournier, R. O., M. Van Det, N. B. Hargraves, J. S. Wilson, T. A. Clair, and R.Ernst. 1984. Physical factors controlling summer distributions of chlorophyll *a* off southwestern Nova Scotia. *Limnol. Oceanogr.*, 29:517-526.

Franks, P. J. S. and C. Chen. 1996. Plankton production in tidal fronts: A model of Georges Bank in summer. *J. Mar. Res.*, 54:631-651.

Galperin, B., L. H. Kantha, S. Hassid, and A. Rosati. 1988. A quasi-equilibrium turbulent energy model for geophysical flows. *J. Atmos. Sci.*, 45:55-62.

Garrett, C. J. R. and R. H. Loucks. 1976. Upwelling along the Yarmouth shore of Nova Scotia. *J. Fish. Res. Board Can.*, 33:116-117.

Garrett, C. J. R., J. R. Keeley, and D. A. Greenberg. 1978. Tidal mixing versus thermal stratification in the Bay of Fundy and Gulf of Maine. *Atmosphere-Ocean*, 16:403-423.

Garrett, C. J. R., and J. W.Loder. 1981. Dynamical aspects of shallow sea fronts. *Phil. Trans. Roy. Soc. London*, A302:563-581.

Gascard J-C. and R. A.Clarke. 1983. The formation of Labrador Sea Water. Part II: Mesoscale and smaller-scale processes. *J. Phys. Oceanogr.*, 13:1779-1797.

Greenberg, D. A. 1983. Modelling the barotropic circulation in the Bay of Fundy and Gulf of Maine. *J. Phys. Oceanogr.*, 13:888-906.

Greenberg, D. A., J. W. Loder, Y. Shen, D. R. Lynch, and C. E. Naimie. 1997. Spatial and temporal structure of the barotropic response of the Scotian Shelf and Gulf of Maine to surface wind stress. *J. Geophys. Res.*, 102(9):20,897-20,915.

Hachey, H. B. 1935. The effect of a storm on an inshore area with markedly stratified waters. *J. Biol. Board Can.*, 1:227-237.

Hannah, C. G., C. E. Naimie, J. W. Loder, and F. E. Werner. 1997. Upper-ocean transport mechanisms from the Gulf of Maine to Georges Bank, with implications for Calanus supply. *Cont. Shelf Res.*, in press.

Harrison, W. G., E. P. W. Horne, B. Irwin, and T. Platt. 1990. Biological new production on Georges Bank: Are tidal fronts primary sources of new production in summer? *EOS Trans. AGU*, 71, 96.

Hopkins, T. S. and N. Garfield III. 1979. Gulf of Maine Intermediate Water. *J. Mar. Res.*, 37:103-139.

Hopkins, T. S. and N. Garfield III. 1981. Physical origins of Georges Bank water. *J. Mar. Res.*, 39:465-500.

Horne, E. P. W., J. W. Loder, W. G. Harrison, R. Mohn, M. R. Lewis, B. Irwin, and T. Platt. 1989. Nitrate supply and demand at the Georges Bank tidal front. *Topics in Marine Biology, Scient. Mar.*, 53:145-158.

Horne, E. P. W., J. W. Loder, C. E. Naimie, and N. S. Oakey. 1996. Turbulence dissipation rates and nitrate supply in the upper water column on Georges Bank. *Deep Sea Res. II., Topical Studies in Oceanography,* Physical-Biological Interactions on Georges Bank and its Environs, 1683-1712.

Lamb, K. G. 1994. Numerical experiments of internal wave generation by strong tidal flow across a finite amplitude bank edge. *J. Geophys. Res.,* 99:843-864.

Lauzier, L. M. 1967. Bottom residual drift on the continental shelf area of the Canadian Atlantic Coast. *J. Fish. Res. Board Can.,* 24:1845-1858.

La Violette, P. E. Johnson, and D. A. Brooks. 1990. Sunglitter photographs of Georges Bank and the Gulf of Maine from the space shuttle. *Oceanogr.,* 3:43-49.

Loder, J. W. and C. Garrett. 1978. The 18.6-year cycle of sea surface temperature in shallow seas due to variations in tidal mixing. *J. Geophys. Res.,* 83:1967-1970.

Loder, J. W. and D. A. Greenberg. 1986. Predicted positions of tidal fronts in the Gulf of Maine region. *Cont. Shelf Res.,* 6:397-414.

Loder, J. W. and E. P. W. Horne. 1991. Skew eddy fluxes as signatures of nonlinear tidal current interactions, with application to Georges Bank. *Atmosphere-Ocean,* 29:517-546.

Loder, J. W., D. Brickman, and E. P. W. Horne. 1992. Detailed structure of currents and hydrography on the northern side of Georges Bank. *J. Geophys. Res.,* 97:14331-14351.

Loder, J. W., R. I. Perry, K. F. Drinkwater, J. Grant, G. C. Harding, W. G. Harrison, E. P. W. Horne, N. S. Oakey, C. T. Taggart, M. J. Tremblay, D. Brickman, and M. M. Sinclair. 1992b. Physics and biology of the Georges Bank frontal zone. In *Science Review, 1990 & '91.,* DFO, 57-61.

Loder, J. W., K. F. Drinkwater, N. Oakey, and E. P. W. Horne. 1993. Circulation, hydrographic structure and mixing at tidal fronts: a view from Georges Bank. *Phil. Trans. Roy. Soc. London,* A343:447-460.

Loder, J., Y. Shen, and H. Ridderinkhof. 1997. Characterization of three-dimensional Lagrangian circulation associated with tidal rectification over a submarine bank. *J. Phys. Oceanogr.,* 27(8):1729-1742.

Lynch, D. R., J. T. C. Ip, C. E. Naimie, and F. E. Werner. 1996. Comprehensive coastal circulation model with application to the Gulf of Maine. *Cont. Shelf Res.,* 16:875-906.

Mellor, G. L. and T. Yamada. 1982. Development of a turbulence closure model for geophysical problems. *Rev. Geophys. Space Physics.,* 20:851-875.

Meise, C. and J. E. O'Reilly. 1996. Spatial and seasonal patterns in abundance and age composition of *Calanus finmarchicus* in the Gulf of Maine and on Georges Bank: 1977-1987. *Deep Sea Res. II., Topical Studies in Oceanography,* Physical-Biological Interactions on Georges Bank and its Environs, 1473-1502.

Mountain, D. G. and P. F. Jessen. 1986. Bottom waters of the Gulf of Maine, 1978-1983. *J. Mar. Res.,* 45:319-345.

Naimie, C. E. 1996. Georges Bank residual circulation during weak and strong stratification periods - Prognostic numerical model results. *J. Geophys. Res.,* 101:6469-6486.

Naimie, C. E., J. W. Loder, and D. R. Lynch. 1994. Seasonal variation of the 3-D residual circulation on Georges Bank. *J. Geophys. Res.,* 99:15,967-15,989.

Oakey, N.S. 1988 EPSONDE: an instrument to measure turbulence in the deep ocean. *IEEE Journal of Oceanic Engineering,* 13:124-128.

Perry, R. I., G. C. Harding, J. W. Loder, M. J. Tremblay, K. F. Drinkwater, and M. M. Sinclair. 1993. Zooplankton distributions at the Georges Bank frontal system: retention of dispersion?, *Cont. Shelf Res.,* 13:357-383.

Petrie, B. 1983. Current response at the shelf break to transient wind forcing. *J. Geophys. Res.,* 88:9567-9578.

Petrie, B., B. J. Topliss, and D. G. Wright. 1987. Coastal upwelling and eddy development off Nova Scotia. *J. Geophys. Res.,* 29:12,979-12,991.

Schwing, F. B. 1992a. Subtidal response of Scotian Shelf circulation to local and remote forcing. Part I: Observations. *J. Phys. Oceanogr.,* 22:523-541.

Schwing, F. B. 1992b. Subtidal response of Scotian Shelf circulation to local and remote forcing. Part II: Barotropic model. *J. Phys. Oceanogr.,* 22:542-563.

Schlitz, R. J. and E. B. Cohen. 1984. A nitrogen budget for the Gulf of Maine and Georges Bank. *Biolog. Oceanogr.,* 3:203-222.

Simpson, J. H. and J. R. Hunter. 1974. Fronts in the Irish Sea. *Nature,* 250:404-406.

Simpson, J. H. and D. Bowers. 1981. Models of stratification and frontal movement in shelf seas. *Deep-Sea Research,* 28A:727-738.

Smith, P. C. 1978. Low-frequency fluxes of momentum, heat, salt, and nutrients at the edge of the Scotian Shelf. *J. Geophys. Res.,* 83:4079-4096.

Smith, P. C. 1983. The mean and seasonal circulation off southwest Nova Scotia. *J. Phys. Oceanogr.,* 13:1034-1054.

Smith, P. C. and J. I. MacPherson. 1987. Cross-shore variations of near-surface wind velocity and atmospheric turbulence at the land-sea boundary during CASP. *Atmosphere-Ocean,* 25:279-303.

Stommel, H. 1972. Deep wintertime convection in the western Mediterranean Sea. *Wust Memorial Volume*, Columbia University.

Tee, K-T. 1979. The structure of three-dimensional tide-generating currents. Part I: Oscillating currents. *J. Phys. Oceanogr.*, 9:930-944.

Tee, K-T. 1980. The structure of three-dimensional tide-generating currents. Part II: Residual current. *J. Phys. Oceanogr.*, 10:2035-2057.

Tee, K-T. 1987. Simple models to simulate three-dimensional tidal and residual currents. Three-dimensional coastal ocean models. *Coast. Estuarine Sci.*, 4:125-147.

Tee, K-T, P. C. Smith and D. Lefaivre. 1987. Modelling and observations of the residual current off southwest Nova Scotia. *Proc. Eighteenth Int. Liege Colloq. on Ocean Hydrodynamics*, Elsevier Oceanogr. Ser., 45:455-470.

Tee, K-T, P. C. Smith and D. Lefaivre. 1988. Estimation and verification of tidally induced residual currents. *J. Phys. Oceanogr.*, 18:1415-1434.

Tee, K-T, P. C. Smith and D. Lefaivre. 1993. Topographic upwelling off southwest Nova Scotia. *J. Phys. Oceanogr.*, 23:1703-1726.

Werner, F. E., R. I. Perry, R. G. Lough, and C. E. Naimie. 1996. Trophodynamic and advective influences on Georges Bank larval cod and haddock. *Deep Sea Res. II., Topical Studies in Oceanography*, Physical-Biological Interactions on Georges Bank and its Environs, 1793-1822.

Small-Scale Biological-Physical Interactions

Lewis S. Incze
Bigelow Laboratory for Ocean Sciences

Abstract

This brief synthesis examines recent developments in the field of small-scale biological-physical interactions in the water column, especially the development of "turbulence theory" in plankton ecology, introduced in 1988, and observations of turbulence-enhanced feeding rates in field and laboratory studies, mostly since 1990. Evidence supports the idea that mixing has a strong positive impact on feeding by some organisms, and attempts to explain this in terms of increased encounter rates have led to more critical examinations of animal behavior and more sophisticated treatment of feeding interactions in models. This work is in early stages, however. The full range and complex spatial and temporal patterns of turbulence in the field are difficult to measure, and in the laboratory turbulence is supplied over a narrow range compared to that in the ocean. Intermittency of turbulence must lead to patchiness of organisms and vorticity on many scales; thus, spatial and temporal aspects of patch structures and behavioral responses of predators and prey to a variety of sensory inputs must be considered. New sampling methods, especially video recording, have been instrumental to recent progress and can help link statistical descriptions of patch size and organism responses to larger scale forcing.

Introduction

The definition of small-scale is somewhat arbitrary; I shall define it here as $\leq$ 1 m so that the upper boundary includes the present limits of resolution for many biological observations made in the water column, especially those relating to zooplankton and larval fish. Pump sampling is generally limited to about 1 m resolution at best because of relative motion between the intake and surrounding water and the sample volume requirements. In practice, pumping yields discrete samples which average from collections over more than a 1-m length scale, but the technique nonetheless is useful when examining features with steep (m-scale) property gradients in one dimension, such as vertical profiles through pycnoclines or horizontal comparisons across Langmuir circulations or other small frontal phenomena. It also offers simplicity and speed over some of the other options for bulk water sampling (Incze et al. 1996). Video sampling has the great benefit of providing virtually continuous data with reasonably high taxonomic resolution and small distortion of the sampled volume. While the data present a daunting challenge for "sample processing", they can provide great insight into the spatial arrangement of organisms on a number of size scales affected by physical forcing, since the sampling rate is high and records may extend for several kilometers (Davis et al. 1992b). Even so, large inter-organism spacing and the high magnification (small volume) required for *in situ* viewing introduce problems in applying these techniques to less-abundant species (Benfield et al. 1996). Other common methods of sampling either compromise on taxonomic information (such as particle counting, acoustics) or spatial resolution (such as nets), although these serve other, essential functions in plankton studies. I will return to video and other sampling efforts at the end of this paper, particularly to report on recent advances based on work in the Gulf of Maine. Much of this overview, however, is dedicated to emerging information and ideas concerning smaller scales (mm to cm in size) at which organisms interact and where the smallest scales of turbulence and shear are active. The examples most often given concern small larval fish feeding on copepod nauplii because this interaction currently encompasses the broadest range of investigation, including early theoretical treatment, field observation, laboratory study (including rates and behavior) and modeling. The implications have broad relevance to other possible interactions as well, and references to other organisms and work are made at appropriate times.

The "Dissipation" Scale

Turbulence is generated primarily by wind mixing, convection and breaking waves at the surface; by shear instabilities within the stratified interior of the ocean; and in coastal seas by tidal and other forcing along the bottom. Energy is transferred across an inertial range of decreasing eddy sizes until variations in velocity become dampened by molecular viscosity. The scale of the smallest motions depends on the amount of energy supplied, and at that scale the transfer rate of turbulent kinetic energy is assumed equal to the dissipation rate, ε, commonly expressed in units of W kg^{-1}. The smallest shear is considered by physical oceanographers to be the Kolmogorov length:

$$\eta = (\nu^3/\varepsilon)^{0.25} \qquad (1)$$

where ν = kinematic viscosity (about 1.05×10^{-6} m^2 s^{-1}) and ε = the dissipation rate of turbulent kinetic energy, which in the ocean is found mostly in the range 10^{-5} - 10^{-9} W kg^{-1}. The higher the energy, the smaller the minimum eddy scale associated with it; at the above dissipation rates, η ranges from 0.06 - 0.6 cm, respectively.

The small scale of structure and motion in the sea has been of interest to physical oceanographers for a long time because of its role in completing the transfer of momentum and mass. Until recently, it was necessary to parameterize small-scale processes in terms of larger grid-scale variables whose further resolution was limited by measurement techniques. This left an incomplete and tenuous picture of the ocean because the small-scale mixing coefficients had to be inferred and manipulated in order to force agreement with observed density and velocity fields at larger scale (Price et al. 1987). The absence of measurements and verifiable theory at this small scale is generally referred to as the "turbulence closure problem." Instrument development beginning in the mid 1950s has led to the current ability to measure temperature and velocity variability at cm scale in the oceans (Oakey and Elliott 1982; see review by Gregg 1991). The growing volume of measurements continues to challenge theories about turbulence from a purely physical viewpoint (Gargett 1989), but the topic and measurement techniques are now more established than new. Advances in modeling and computational capability have led to the inclusion of advanced turbulence closure schemes which incorporate turbulent kinetic energy and mixing length as hydrodynamic state variables. Recently, trophodynamic, "individual-based" submodels have been added to physical models in order to study the coupled effects of advection, mixing, vertical behavior, prey concentration and small- (turbulence-) scale mixing on the distribution, feeding, growth and survival of organisms (Werner et al. 1996). Theoretical biological thinking about the ecological effects of turbulence is not new (Margalef et al. 1979), but the modern literature on coupled biological-physical processes which include theory and measurements at turbulence-scale begins in 1988, and the majority of papers have been published since 1990.

Lynch et al. (1995) describe a comprehensive circulation model for the Gulf of Maine with advanced turbulence closure (Mellor and Yamada 1982) that can produce profiles of turbulent kinetic energy (TKE) dissipation rate. A recent study of Georges Bank found that model predictions of ε were in fairly close agreement with values derived from field measurements of velocity shear microstructure for conditions where tidal shear dominated the mixing (Horne et al. 1996). In an earlier paper, MacKenzie and Leggett (1993), who were interested in depth-dependent effects of mixing on larval fish feeding, examined empirical fits for wind-generated mixing in the surface layer based on a boundary layer model (Oakey 1985). Their results indicate the model is broadly useful and robust: of about 800 profiles of TKE from fourteen geographic areas, the model accounted for 58% of the observed variation. Sixty-eight percent of the observations fell within a factor of five of model predictions even in areas (n=270 profiles) where other sources of turbulence were known to exist. This is not a very wide margin considering the five-decade range of turbulence in the upper ocean. This is not to say that refinement would not be desirable, but taken together, the agreement among model calculations, a simple empirical calculation for the wind-mixed layer, and a growing number of field measurements is encouraging of efforts to couple the small-scale turbulence to larger-scale forcing and to small-scale trophodynamic effects in models (Davis et al. 1991, Werner et al. 1996) and field work (Muelbert et al. 1994, Incze et al. 1996, Lough and Mountain 1996). In both theory and measurement, physical and biological, there is much yet to do (Gargett 1989, Denman and Gargett 1995), but the current state of affairs provides rich ground for exploring biological-physical coupling at small scale. In the paragraphs that follow, I will examine briefly the theory behind trophodynamic, biological-physical interactions; evidence supporting their importance; and some thoughts about future research.

Small-Scale Biological-Physical Interactions: Theory and Evidence

Rothschild and Osborn (1988) introduced the idea that small-scale turbulence can enhance encounter rates between an organism and its prey by adding, isotropically and randomly, to the relative speed between particles. The general form of the relationship, incorporating a modification by Evans (1989), is:

$$A = (u^2 + v^2 + 2\omega^2)^{0.5} \qquad (2)$$

where u and v are the speed of prey and predator, respectively, and ω is the turbulent velocity at a length scale appropriate to the predator-prey interaction. The prey speed is usually insignificant compared to predator speed and in practice is often dropped; I retain it here and throughout the following discussion so the concept is not overlooked. Continuing in the next two equations as Rothschild and Osborn proposed, the rms turbulent velocity is derived from the dissipation rate (ε) at an appropriate length scale (d) of interest:

$$\omega^2 = 3.615(\varepsilon d)^{2/3} \qquad (3)$$

Finally, A (Equation 2) is used in a model of predator-prey encounter to predict an encounter rate (E, the same as the "contact rate" of Gerritsen and Strickler 1977):

$$E = (\pi R^2 N)A \qquad (4)$$

where R is the encounter radius of the predator and N is the number of prey per unit volume. The encounter radius can be thought of as the sensory limit for visual, chemical or mechanical detection or as the range of influence of feeding currents for suspension feeders.

The point of these equations is to illustrate the general nature of the theory; no effort is spent here in their derivation and little on their nuances. Several points must be noted, however. First, it is obvious that the turbulent velocity calculation (Equation 3) is sensitive to the selection of length scale. The perceptive distance of the predator has gained currency as a realistic value to use (Evans 1989, Denman and Gargett 1995, Kiorboe and MacKenzie 1995) because to be useful in the context of Equations 2 and 4, turbulent motions must assist in bringing a prey within the detection range of the predator. Second, the speed of the predator (Equation 2) affects the relative contribution that turbulence can make to encounter frequency, so predator speed must be well known. Even in a non-turbulent environment the swimming speed and behavior of the predator and the geometry of its perceptive field (expressed in Equation 4) are more complicated than expressed by the simplified equations above (MacKenzie and Kiorboe 1995). A point of confusion may readily arise by thinking of the swimming speed difference (A) as a linear process; it is not. The motion of the two particles is independent until the two are within a detection range (either the predator's for pursuit or the prey's for escape); the addition of turbulence is akin to energizing gas particles in a fixed volume. Third, ε is not a constant at any spot in the ocean, but is highly intermittent, thus varying the first-order effects on relative speed (A) as well as any secondary effects on organism behavior (e.g., swimming activity, perception, reaction times) and on the dispersion and patchiness of prey (see later discussion).

Rothschild and Osborn's introduction of "turbulence theory" into plankton ecology in 1988 has stimulated a considerable body of useful work and speculation (see reviews by Denman and Gargett 1995, Dower et al. 1997) and it has reinvigorated laboratory studies of feeding rates and behaviors, many of which now introduce environmentally meaningful levels of turbulence into experiments, at least at the immediate length scales of organism interactions. [This is an important distinction to which I return later.] Expanded application of video technology permits detailed quantification of reactive distance and feeding strategy (Kiorboe and Saiz 1995, MacKenzie and Kiorboe 1995, Saiz and Kiorboe 1995), with the result that increasingly critical questions about organism behavior, the distribution of turbulent energy at relatively small scales in the environment, and appropriate applications of laboratory data and "turbulence theory" to the field are being asked (Osborn 1996). It should be pointed out here that the equations thus far deal only with encounter and not with the complex features of pursuit, success of capture, handling time, and subsequent modifications to search behavior (MacKenzie et al. 1994). Also, the benefit to the predator of enhanced encounter rate is not uniform across all prey densities; in theory as well as observation, turbulent enhancement of feeding decreases as satiation feeding conditions are approached. Finally, the possibility of a hyperbolic relationship exists at higher turbulence levels (Jenkinson and Wyatt 1992, MacKenzie et al. 1994), although evidence for this remains weak (Sundby et al. 1994, Kiorboe and Saiz 1995). Where strong wind mixing has been implicated in poor larval survival in the field, the underlying cause-effect relationship can be difficult to discern (Bailey and Macklin 1994). Animals may respond to transient undesirable levels of turbulence by adjusting their position in the water column (Kendall et al. 1994). Such behavior may have positive consequences over all even if feeding is temporarily diminished. Turbulence can be expected to affect many, if not all, trophic levels of the plankton and the effects should be manifested over different time scales (e.g., nutrient injections and changes in light regime may affect phytoplankton growth for many days); narrow interest in larval fish feeding interactions during transient events cannot ignore the broader context of planktonic community dynamics which may be favorable over longer time periods.

Sundby and Fossum (1990) conducted one of the first field tests of the Rothschild and Osborn hypothesis by examining the stomach contents of cod larvae in the Lofoten area, northern Norway, using historical collections (1976-1984) which included data on wind speed, concentrations of prey (copepod nauplii), and hydrography. Plotting the feeding ratio against naupliar densities for various wind strengths over the previous 8 h, they found increased feeding with increased average wind speed up to the upper limit contained in their data: feeding increased by 2.8 x as the 8-h average wind for the various collections increased from 2 to 6 m s^{-1}. Subsequent work (Sundby et al. 1994) expanded the data set to include a larger number of larvae, higher wind speeds, and a consideration of added turbulence due to tidal mixing. The data corroborate the general nature of their earlier findings, with somewhat greater enhancements. These calculations are "model-independent" as they refer only to observed feeding ratios and environmental conditions. As a test of the "turbulence theory", the authors used the model in Equations 2 & 4 and predicted enhancements in encounter rate on the order of 2.2 x for the increase from 2-6 m s^{-1} winds. Given the simplifying assumptions of the model, its sensitivity to various parameter values (see above), and continuing uncertainty (or at least controversy) regarding the appropriate length scale, the agreement is quite good and suggests that turbulence may be directly responsible for some of the observed increases in feeding. [Note: Sundby and Fossum used the average separation distance of prey for estimating shear: see original arguments by Rothschild and Osborn 1988.]

Non-linearities involved in turbulence calculations make clear the need for improved understanding of biological behaviors, however. MacKenzie and Kiorboe (1995) elaborated on the encounter model for cod by quantifying the pause-travel nature of its swimming and searching behavior. They found:

$$E=(2/3\pi R^3N*PF)+(\pi R^2N(\upsilon^2+2\omega^2)^{0.5}*PF*PD \quad (5)$$

where PF = pause frequency, PD=pause duration (in seconds), and other variables are the same as in earlier equations. Note the change in geometry of the perceptive field from Equation 4. The calm water average swimming speed (averaged for swimming bouts and pausing), at 0.17 cm s^{-1}, is slightly less than the average used before. This similarity is deceiving, however: the larva searches when still, not when cruising (this decreases the predicted encounter rate), but the video studies show a greater perceptive distance than used in earlier calculations (which increases the encounter rate). The net result is a small increase in the predicted encounter rate in calm water compared to earlier versions. These modifications of the formula for describing laboratory feeding could have been made without considering turbulence; the real importance of the more sophisticated model emerges when considering feeding in turbulent conditions.

The authors found significant increases in encounter rate in turbulent compared to calm laboratory conditions for early feeding cod larvae. Encounters in turbulent conditions (prey density < 35 l^{-1}, ε 10^{-7} W kg^{-1}—both realistic field values) were approximately 2.2 x those in calm conditions. Like the field data of Sundby and Fossum (1990) and Sundby et al. (1994), these results are model-independent and indicate that including turbulence is an important aspect of measuring planktonic rates even if our knowledge of the underlying mechanisms is incomplete. Using Equation 5 to predict the enhancement of encounter rates due to turbulence, the authors found that calculations overestimated the observations: 3.2 x predicted *vs.* an average of 2.2 x observed. These differences are not surprising given uncertainties that remain with the theory and scaling arguments and the fact that models still simplify and average the activity of animals. It is significant that the studies document shifts in pause frequency with turbulence: PF went from 26.0 min^{-1} in calm water to 29.7 min^{-1} in turbulent water, with a corresponding shift in pause duration from 2.0 to 1.7 s. Manipulation of the equations shows that this change in behavior is an important contributor to the increased encounter rates. Changes in predator behavior due to turbulence, prey concentration and hunger all must be considered as one moves from laboratory rates to a prediction of field interactions and feeding (MacKenzie and Kiorboe 1995, their Table 1; Munk 1995) and an understanding of animal distributions and dynamics.

Predators may be broadly classified as ambush (pause-travel may be considered a variant of this) or cruising (Greene 1985; O'Brien et al. 1990). Without much further elaboration, it is worth drawing attention to the model MacKenzie and Kiorboe (1995; hereafter M&K) devised for herring larvae, which are cruising predators:

$$E = 0.5\,\pi\,R^2 N^* SA\ * (u^2 + v^2 + 2\,\omega^2)^{0.5} \qquad (6)$$

where SA = proportion of time swimming and other variables are as reported earlier. In this case, the predator detects prey while swimming and the model more closely resembles that put forward in Equation 3, which is a "volume swept" calculation. The proportion of time that herring spent swimming/searching (35-48% in M&K's experiments) is less than the time cod spent pausing/searching (84-88%), but the volumes searched have a different set of dependencies. The two data sets are not directly comparable because larvae of the two species were of different sizes and their sensory modalities do not necessarily undergo completely parallel development, but these model distinctions suggest the refinement of ideas and measurements needed to understand interspecific differences in particle-feeding rates in the ocean.

To conclude this section on evidence for turbulent enhancement of feeding, I turn briefly to a consideration of copepods and then protozoans. Kiorboe and Saiz (1995) provide a general discussion of suspension- and particle-feeding by copepods in calm and turbulent conditions feeding on phytoplankton and ciliates. Their discussion employs a concept of feeding volumes which relieves the calculations of the often unrealistic assumption of straight-line swimming and replaces it with a "diffusion" rate for predators and their prey. Theoretical considerations indicate that realistic levels of small-scale turbulence should have negligible effects on suspension-feeding because the feeding currents have high shear and in most cases do not extend far from the predator's body: unrealistically high turbulence would be required to operate at these scales in either an augmenting or disrupting process. Osborn (1996) argues, however, that larger-scale turbulence may be important for maintaining a high ambient supply of cells at the periphery of the feeding current and reducing the need for swimming. For copepods in particle-feeding mode, there appear to be potentially large impacts on feeding rate. Theory fits well with observational data showing changes in behavior and increased feeding rate of *Acartia* spp. when preying on ciliates and dinoflagellates at increased levels of turbulence (Saiz and Alcarez 1992, Kiorboe and Saiz 1995).

There is ongoing debate about the physical nature of turbulence and biological interactions at the smallest scales. It has been argued that the smallest feature of direct impact on feeding interactions is larger than the Kolmogorov scale (the viscous length scale) by a factor of 2 (Lazier and Mann 1989, Denman and Gargett 1995). At this time, however, neither theory nor observation can accurately address what happens at this small scale (Hill et al. 1992), and anisotropic turbulence and sub-eddy shearing might also lead to enhanced feeding when coupled with specific foraging behaviors. Part of the answer must lie in the size of the organisms themselves. Shimeta et al. (1995) report elevated feeding by protozoan suspension feeders at moderate laminar shears (e.g. $< 5\ s^{-1}$) smaller than the turbulence microscale.

Patchiness

One shortcoming of laboratory experiments using turbulence is that they contain a small range of dissipation values, whereas in nature turbulence is notoriously patchy or intermittent in intensity and spans several decades (Gargett et al. 1984). The spatially patchy dis-

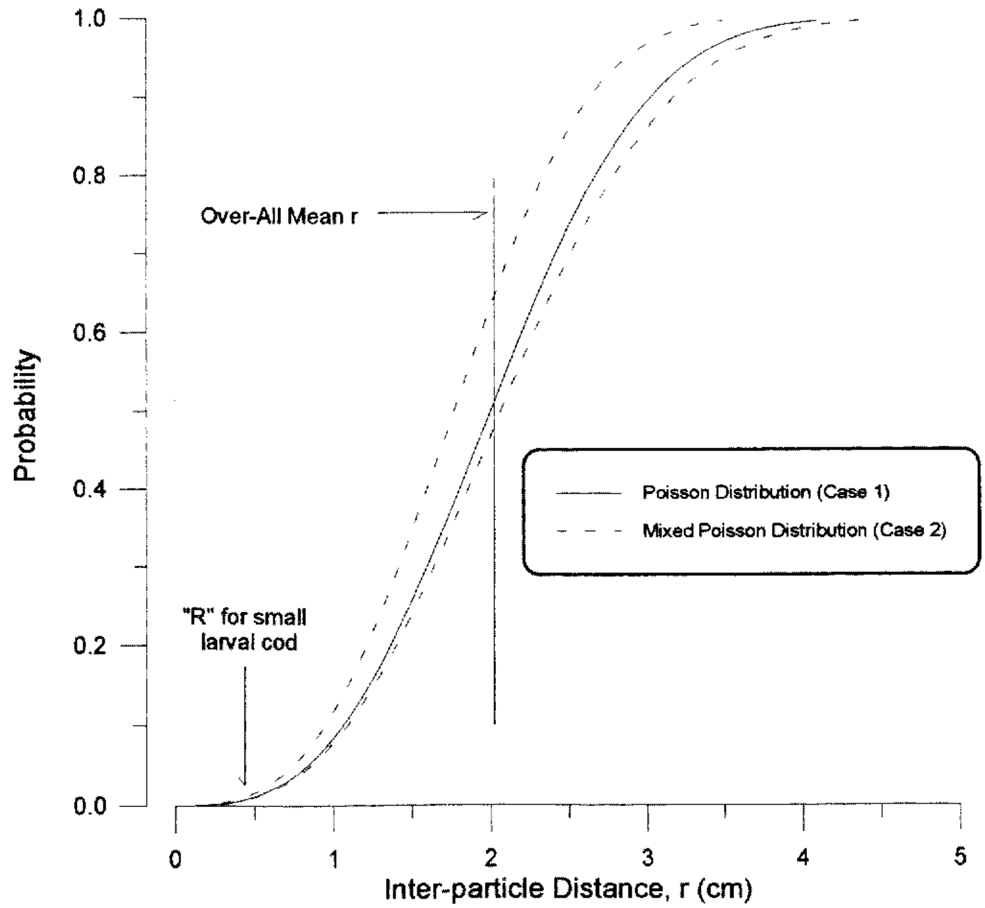


Figure1. Cumulative probability distributions for interparticle distances between copepod nauplii at a mean over-all concentration ($\bar{\lambda}$) of 20 l^{-1} using Poisson (Case 1) and mixed-Poisson (Case 2) distribution functions. Note that the concentration is prescribed, but not the volume; the naupliar concentration is common for the stratified area of Georges Bank when cod larvae are beginning to feed. In Case 1, the mean inter-particle distance is just over 2 cm. In Case 2, 20% of the volume is comprised of a patch or patches in which the concentration of nauplii (λ_2) is 1.5 x the over-all mean ($v = 0.2$, $\lambda_2 = 1.5 \times \bar{\lambda}$, or 30 nauplii l^{-1}). The total number of nauplii is the same as in Case 1. These patches would be difficult to detect when sampling unless they were quite large, yet they offer an 18% increase in the probability of finding particles within the over-all mean separation distance (r). Another way to look at this is that the 50% probability occurs at a shorter distance, and therefore a shorter foraging time. For scaling, the perceptive radius (R) for small cod larvae is shown. Using the pause-travel model of MacKenzie and Kiorboe (1995) and the Poisson distribution of prey in calm water, a cod larva has a 50% probability of encountering a nauplius within 8 min (E=0.125 min^{-1}). These time and space dimensions must be considered when describing what a "patch" looks like to a foraging cod larva and evaluating the relative role of patch structures *vs.* enhancements due to turbulence. Field and laboratory data indicate greater enhancements due to turbulence than the patch case described here with no turbulence. At $\varepsilon = 10^{-7}$ W kg^{-1}, the dimension $2\pi\eta$ is less than the perceptive radius of the cod larva; and at a distance, *d*, equal to the perceptive radius, R, the turbulent velocity ω is >50% of the average swimming speed of the larva (see text and Equation 3 for relevance).

tribution of mixing energy, both at the large forcing scales and the dissipative, turbulence scales, can create plankton patches through at least two mechanisms. First is the uneven redistribution of patterns established through other previous and ongoing means, both biological and physical. In the simplest illustration, layers may be disrupted, leaving patches behind, and aggregations may be displaced to new regions, introducing patches. Each displacement creates a local environment of enhanced shear and the new structures are themselves modified by subsequent physical forcing and by biological consequences of the new patterns created. The problem is obviously multi-dimensional and only limited aspects of it can be subjected to laboratory investigation at any one time. Second, there are coherent scales even within turbulent structures and these may be most pro-

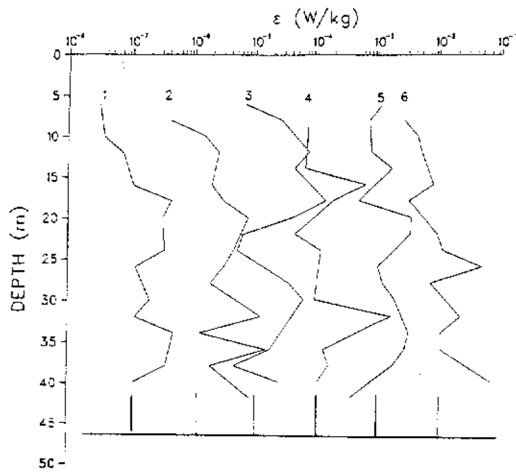


Figure 2a. A series of individual turbulence profiles illustrating variability of turbulence measurements over short time periods. Profiles were collected within a 30-minute sampling burst in the mixed area, northern Georges Bank in August 1985. Successive profiles are offset 1 order of magnitude to the right. Some depth intervals (e.g., ca. 15 -17 m, 30-35 m) show more than an order of magnitude variation in the series.

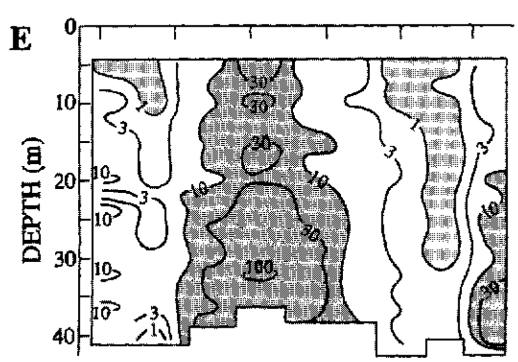


Figure 2b. Variations in burst-average water column dissipation rate profiles over a tidal period. (Both illustrations are from Horne et al. 1996, with permission).

nounced at the smallest scales of flow, the Kolmogorov scales (Squires and Yamazaki 1995), forming not only localized and transient aggregations of organisms (such as prey), but also complex vorticity fields. Since these are part of the natural background, organisms presumably are adapted to orienting and operating about these structures in ways that enhance vital functions such as finding prey (Yamazaki et al. 1991, Jenkinsen and Wyatt 1992, Yamazaki 1993). It is possible that patches and patch-oriented behaviors contribute to elevated feeding levels seen in turbulent conditions, and this possibility demands that one consider patchiness and appropriate probability distribution functions on small scales (Rothschild 1992). A relative scaling of processes for larval cod feeding on copepod nauplii is shown in Figure 1, but this is a static view that does not incorporate flexible behavior or the real distribution of prey and turbulence on many scales. It will take many approaches, including laboratory, field and modeling efforts, to get a quantitative feel for the small-scale interactions that are taking place and how these relate to larger organized structures and the ongoing periodic and aperiodic forcing at larger scales.

Turbulence Measurements, Modeling and Applications in the Gulf of Maine

Several sets of turbulence measurements based on microscale velocity shear are presently available in the Gulf of Maine, all on Georges Bank during periods of light wind (Oakey and Petipas 1992, Loder et al. 1993, Yoshida and Oakey 1996, Horne et al. 1996; Burgett et al. 1996). Data fall within the range of most oceanic observations: 10^{-5} to 10^{-9} W kg^{-1}. Because microscale turbulence is highly variable, measurements usually are made in a rapid series of profiles which are then binned over shallow, e.g., 1 m, depth intervals to generate characteristic dissipation rate profiles and statistics for each group of profiles (the group is called a "sampling burst"). Sampling bursts are then repeated at the desired frequency to sample tidal, meteorological or other temporal modifications. Variability of individual profiles within a sampling burst (Figure 2a) shows dissipation rate varying by more than an order of magnitude within several depth ranges over a period of less than 30 minutes. Since water was being advected past the anchored sampling vessel at a rate that varied with depth and was similar to the profiler descent rate, it can be seen that individual dissipation rate profiles provide only "snapshots" of turbulence at each depth interval. The minimum length scale of intermittency is not revealed by the data and the range of intensity itself is likely underestimated. An appreciation for the complexity of the task of describing the turbulence field can be gained from reviews by Thorpe (1987), Gregg (1987), Hopfinger (1987), and Gibson (1987). Figure 2b shows a >2 order of magnitude change in ε with tidal period at a single anchor station on Georges Bank.

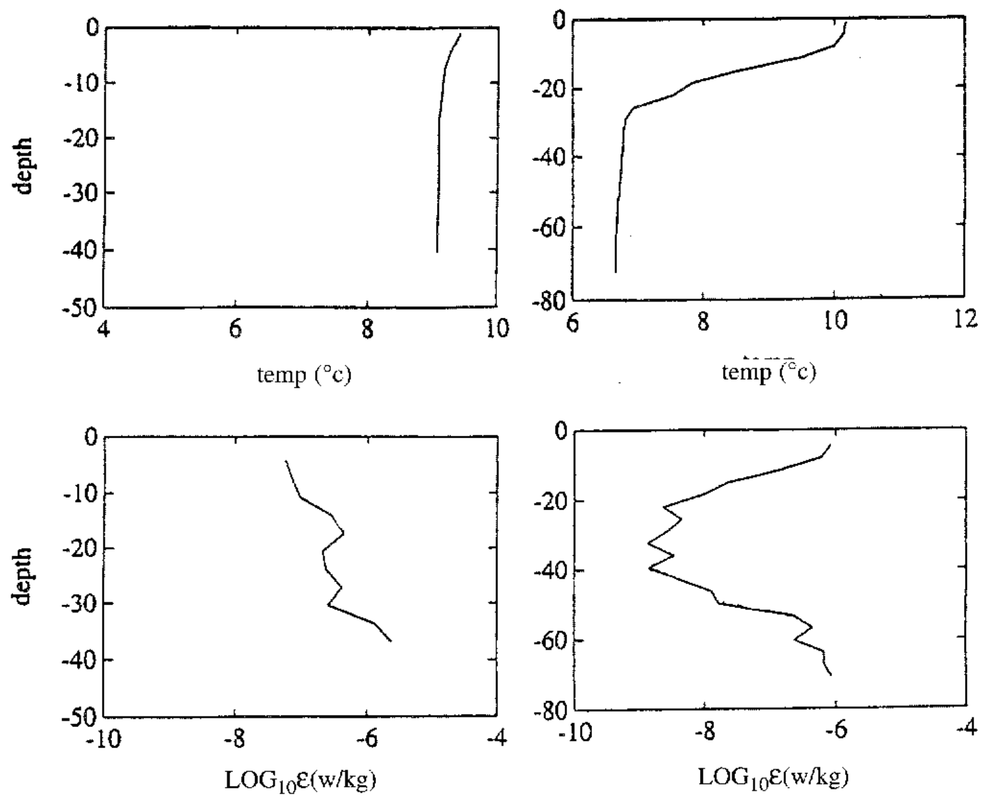


Figure 3. Temperature (upper panels) and burst-average dissipation rate profiles (lower panels) from a station in the mixed area (left column) and stratified area (right column) of Georges Bank during late May, 1995. The mixed area dissipation rate profile shows maximum near bottom (~6 x 10^{-5} W kg^{-1}) due to tidal shear, with a gradual decay toward the surface. The stratified area profile shows a dissipation rate minimum (~10^{-9} W kg^{-1}) in the pycnocline and the area below it. (N. Oakey, unpubl. data, GLOBEC Cruise Report SJ95008, with permission).

Representative profiles of sampling bursts from the mixed area and the weakly stratified area of Georges Bank in May 1995 are shown in Figure 3. The profiles come from periods with light winds, and thus reflect mostly tidally-generated turbulence in the bottom layer (to near surface in the mixed area of the bank), moderate levels of turbulence in the surface layer of the stratified area, and low levels of turbulence in the pycnocline and the region just below. Horne et al. (1996) show that turbulence data respond to the circadiel and lunar monthly tidal periods and that wind can be a significant factor determining mixing even in the tidally well-mixed region near the top of the bank.

Turbulence profiling is specialized work currently requiring significant personnel time and wire time in data collection and processing; thus, it is not a trivial add-on to biological cruises. Nonetheless, expansion of turbulence data sets is needed to characterize different oceanographic settings, particularly in terms of intermittency and patchiness, in order to broaden the consideration and testing of turbulence concepts in plankton ecology. Wind-based calculations seem fairly robust for the surface layer, and a growing number of measurements offer at least reasonable estimates for tidal mixing and for pycnoclines. However, a better theoretical and observational basis is needed for tying dissipation rate measurements into larger-scale features such as convergent fronts and buoyancy-driven currents common in the Gulf of Maine (see Gargett 1994). Recent attempts to apply turbulence theory to field studies in the Gulf of Maine include herring in southwestern Nova Scotia (Muelbert et al. 1994) and larval cod (Incze et al. 1996) and cod and haddock on Georges Bank (Lough and Mountain, 1996). All of the studies suggest that further development and testing of turbulence theory will add to our understanding of planktonic processes in important ways.

Models with advanced turbulence closure schemes

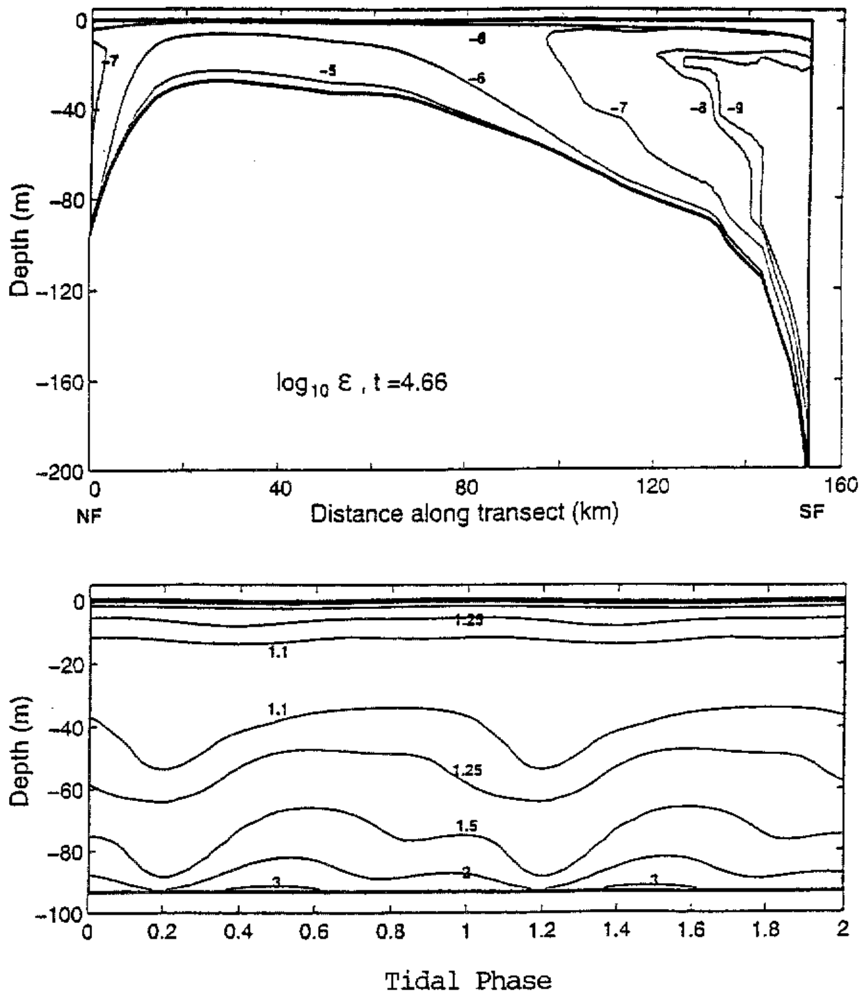


Figure 4. Upper panel: Model output of a vertical cross-section of $\log_{10}$ dissipation rates (W kg^{-1}) across Georges Bank (northern flank on left, southern flank on right) for one step in the tidal phase. Lower panel: Model output of relative enhancement of encounter rate (E_{turb}/E_{calm}) for larval cod on the southern flank of Georges Bank. Tidal phase is marked along the abscissa. (Both illustrations are from Werner et al. 1996, with permission).

are capable of generating realistic average values of dissipation rate at various points in a three-dimensional grid, thus coupling at least average small-scale dynamics to other trophodynamic processes, vertical position in the water column, and advection/diffusion fields. Werner et al. (1996) have recently done this for small-scale turbulence and the feeding, growth, mortality and advection of cod and haddock larvae on Georges Bank. Among the things the model suggests is that turbulent enhancement of feeding is important to the population dynamics of early life stages of cod on the bank. Figure 4 shows an across-shelf transect of tidally-averaged small-scale turbulent dissipation rates and the time-depth structure of feeding enhancements for one modeled scenario. Recall that this does not explicitly address the larger-scale, higher-energy mixing processes or mechanistic links to patch formation. Much still has to be established in order to get the small-scale physics and biology "right", but the capability of putting small-scale processes together with the larger-scale hydrography and circulation in a model represents a significant advancement for exploring ideas and identifying critical areas for research.

Sampling and Other Advances

Zooplankton ecologists interested in coupling small-scale physics with behavior and interactions between organisms face significant sampling problems due to the large range of organism sizes and motility, the comparatively large spaces between organisms relative to the smallest scales of shear, and complex patterns of development and behavior. The problem is obvious when contrasted with the ability to make useful ataxonomic measurements of phytoplankton, by *in vivo* chlorophyll fluorescence, simultaneously and at similar scale with small-scale physical measurements (Cowles and Desiderio 1991). A combination of approaches can help fill the void for zooplankton. The application of video technology to field sampling (Davis et al. 1992a, 1992b, 1996; Ortner 1993; Tiselius et al. 1994; Benfield et al. 1996; Gallager et al. 1996) enables a close examination of spatial structures, organism orientation and other factors important to evaluating responses to environmental conditions and understanding the background against which interactions take place. These undoubtedly will come into greater use and will focus, literally and figuratively, on smaller and smaller organisms. Towed (Davis et al. 1992b), and perhaps moored, video samplers are capable of reasonably long records that can build statistical descriptions of patchiness and responses to forcing at larger scales. These records also can help bridge the data gap between detailed life history studies and the broader-scale but more aggregative sampling techniques such as acoustics (see as examples of these the SCOPEX papers by Wishner et al. 1995 and Macauley et al. 1995, the subjects of which are linked to the higher trophic level of right whales in the southeastern Gulf of Maine).

Summary

The Gulf of Maine has a great variety of physical settings seasonally and spatially, and therefore presents rich ground for considering and exploring small-scale biological-physical interactions. There are implications for both "top-down" and "bottom-up" thinking. Correctly interpreting the effects of physical forcing and of coastal and oceanic settings on the plankton as a whole requires a better understanding of small-scale processes. Conversely, the specific behaviors of some organisms and the kinetics of some processes probably cannot be understood adequately without including turbulence as a variable. I have focused here on fish larvae and their prey because of the volume of recent work available. Particle aggregation and flux (see Jackson 1990, Kiorboe 1993), numerous other zooplankton (e.g., gelatinous zooplankton, many meroplanktonic forms, other copepods) and other environments (the neuston layer, Langmuir cells, fronts, tidal channels) deserve attention. Measuring turbulence and turbulence-mediated rates is specialized work that cannot be as ubiquitous as turbulence itself, but there are many instances where its potential role ought to be considered carefully. Expanded measurements and theoretical development should be broadly useful. Ongoing modeling and sampling efforts in the Gulf of Maine are making important contributions toward a better understanding of small-scale processes and their population-level effects.

Acknowledgments

I have benefited from discussions with Brian MacKenzie, Tom Osborn and Brian Rothschild and from notes shared by Ann Gargett. Neil Oakey, Dave Hebert and John Loder kept me from going too far astray in my interpretations of the physical world at turbulence scale; and Francisco Werner and Greg Lough shared with me their calculations on turbulence and plankton. Despite the best efforts of these colleagues, they cannot be held accountable for my attempt to quickly synthesize the field and suggest directions for future research. I thank Edward Horne and Francisco Werner for permitting the use of some of their figures from recent publications. This synthesis was supported by the Regional Association for Research on the Gulf of Maine and by National Science Foundation grant OCE-9313669.

Pre-publication Addendum

Several short commentaries on effects of turbulence on predator-prey interactions were published recently in *Marine Ecology Progress Series* 139:301-312. These provide further discussions on scaling and organism behavior in clear and easily read text.

References

Bailey, K. M. and S. A. Macklin. 1994. Analysis of patterns in larval walleye pollock *Theragra chalcogramma* survival and wind mixing events in Shelikof Strait, Alaska. *Mar. Ecol. Progr. Ser.* 113: 1-12.

Benfield, M. C., C. S. Davis, P. H. Wiebe, S. M. Gallager, R. G. Lough and N. J. Copley. 1996. Video Plankton Recorder estimates of copepod, pteropod and larvacean distributions from a stratified region of Georges Bank with comparative measurements from a MOCNESS sampler. *Deep-Sea Res. II.* 43: 1925-1946.

Burgett, R., D. Hebert and N. Oakey. 1996. U.S. GLOBEC Georges Bank Microstructure Data. GSO Technical Report No. 96-6, Graduate School of Oceanography, Univ. Rhode Island, Kingston, RI. viii + 414 p.

Cowles, T. J. and R. A. Desiderio. 1993. Resolution of biological microstructure through *in situ* fluorescence emission spectra. *Oceanography* 6: 105-111.

Davis, C. S., G. R. Flierl, P. H. Wiebe and P. J. S. Franks. 1991. Micropatchiness, turbulence and recruitment in plankton. *J. Mar. Res.* 49: 109-151.

Davis, C. S., S. M. Gallager, M. S. Berman, L. R. Haury and J. R. Strickler. 1992a. The video plankton recorder (VPR): Design and initial results. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* 36: 97-108.

Davis, C. S., S. M. Gallager and A. R. Solow. 1992b. Microaggregations of oceanic plankton observed by towed microscopy. *Science* 257: 230-232.

Davis, C. S., S. M. Gallager, M. Marra and W. K. Stewart. 1996. Rapid visualization of plankton abundance and taxonomic composition using the Video Plankton Recorder. *Deep-Sea Res. II*, 43: 1947-1970.

Denman, K. L. and A. E. Gargett. 1995. Biological-physical interactions in the upper ocean: The role of vertical and small-scale transport processes. *Annu. Rev. Fluid. Mech.* 27: 225-255.

Dower, J. F., T. J. Miller and W. C. Leggett. 1997. The role of microscale turbulence in the feeding ecology of larval fish. *Adv. Mar. Biol.* 31:170-220.

Evans, G. T. 1989. The encounter speed of moving predator and prey. *J. Plankton Res.* 11: 415-417.

Gallager, S. M., C. S. Davis, A. W. Epstein, A. Solow and R. C. Beardsley. 1996. High-resolution observations of plankton spatial distributions correlated with hydrography in the Great South Channel, Georges Bank. *Deep-Sea Res. II.* 43: 1627-1664.

Gargett, A. E. 1989. Ocean turbulence. *Annu. Rev. Fluid Mech.* 21: 419-451.

Gargett, A. E. 1994. Observing turbulence with a modified acoustic Doppler current profiler. *J. Atmosph. Oceanic Tech.* 11: 1592-1610.

Gargett, A. E., T. R. Osborn and P. W. Nasmyth. 1984. Local isotropy and the decay of turbulence in a stratified fluid. *J. Fluid Mech.* 144: 231-280.

Gibson, C. H. 1987. Fossil turbulence and intermittency in sampling oceanic mixing processes. *J. Geophys. Res.* 92: 5383-5404.

Greene, C. H. 1985. Planktivore functional groups and patterns of prey selectivity in pelagic communities. *J. Plankton Res.* 7: 35-40.

Gregg, M. C. 1987. Diapycnal mixing in the thermocline: A review. *J. Geophys. Res.* 92: 5249-5286.

Gregg, M. C. 1991. The study of mixing in the ocean: A brief history. *Oceanography* 4: 39-45.

Hill, P. S., A. R. M. Nowell and P. A. Jumars. 1992. Encounter rate by turbulent shear of particles similar in diameter to the Kolmogorov scale. *J. Mar. Res.* 50: 643-668.

Hopfinger, E. J. 1987. Turbulence in stratified fluids: A review. *J. Geophys. Res.* 92: 5287-5303.

Horne, E. P. W., J. W. Loder, C. E. Naimie and N. S. Oakey. 1996. Turbulence dissipation rates and nitrate supply in the upper water column on Georges Bank. *Deep-Sea Res. II*, 43: 1683-1712.

Incze, L. S., P. Aas and T. Ainaire. 1996. Distributions of copepod nauplii and turbulence on the southern flank of Georges Bank: Implications for feeding by larval cod *(Gadus morhua)*. *Deep-Sea Res. II*, 43: 1855-1874.

Jackson, G. A. 1990. A model of the formation of marine algal flocs by physical coagulation processes. *Deep-Sea Res.* 37: 1197-1211.

Jenkinson, I. R. and T. Wyatt. 1992. Selection and control of Deborah numbers in plankton ecology. *J. Plankton Res.* 14: 1697-1721.

Kendall, A. W., Jr., L. S. Incze, P. B. Ortner, S. R. Cummings and P. K. Brown. 1994. The vertical distribution of eggs and larvae of walleye pollock, *Theragra chalcogramma*, in Shelikof Strait, Gulf of Alaska. *Fish. Bull.* 92: 540-554.

Kiorboe, T. 1993. Turbulence, phytoplankton cell size, and the structure of pelagic food webs. *Adv. Mar. Biol.* 29: 1-72.

Kiorboe, T. and E. Saiz. 1995. Planktivorous feeding in calm and turbulent environments, with emphasis on copepods. *Mar. Ecol. Progr. Ser.* 122: 135-145.

Loder, J. W., K. F. Drinkwater, N. S. Oakey and E. P. W. Horne. 1993. Circulation, hydrographic structure and mixing at tidal fronts: the view from Georges Bank. *Phil. Trans. Roy. Soc. A*, 343: 447-460.

Lough, R. G. and D. G. Mountain. 1996. Effect of small-scale turbulence on the feeding rates of larval cod and haddock in stratified water on Georges Bank. *Deep-Sea Res. II*, 43: 1745-1772.

Lynch, D. R., J. T. C. Ip, C. E. Naimie and F. E. Werner. 1995. Comprehensive coastal circulation model with application to the Gulf of Maine. *Cont. Shelf Res.* 16: 875-906.

Macauley, M. C., K. F. Wishner and K. L. Daly. 1995. Acoustic scattering from zooplankton and micronekton in relation to a whale feeding site near Georges Bank and Cape Cod. *Cont. Shelf Res.* 15: 509-537.

MacKenzie, B. R. and T. Kiorboe. 1995. Encounter rates and swimming behavior of pause-travel and cruise larval fish predators in calm and turbulent laboratory environments. *Limnol. Oceanogr.* 40: 1278-1289.

MacKenzie, B. R. and W. C. Leggett. 1993. Wind-based models for estimating the dissipation rates of turbulent energy in aquatic environments: Empirical comparisons. *Mar. Ecol. Progr. Ser.* 94: 207-216.

MacKenzie, B. R., T. J. Miller, S. Cyr and W. C. Leggett. 1994. Evidence for a dome-shaped relationship between turbulence and larval fish ingestion rates. *Limnol. Oceanogr.* 39: 1790-1799.

Margalef, R., M. Estrada and D. Blasco. 1979. Functional morphology of organisms involved in red tides, as adapted to decaying turbulence. In *Toxic Dinoflagellate Blooms* ed. D. L. Taylor and H. H. Seliger, 89-94. New York: Elsevier.

Mellor, G. L. and T. Yamada. 1982. Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.* 20: 851-875.

Muelbert, J. H., M. R. Lewis and D. E. Kelley. 1994. The importance of small-scale turbulence in the feeding of herring larvae. *J. Plankton Res.* 16: 927-944.

Oakey, N. 1985. Statistics of mixing parameters in the upper ocean during JASIN Phase 2. *J. Phys. Oceanogr.* 15: 1662-1675.

Oakey, N. and J. Elliott. 1982. Dissipation within the surface mixed layer. *J. Phys. Oceanogr.* 12: 171-185.

Oakey, N. S. and Pettipas. 1992. Vertical mixing rates on Georges Bank during June-July and October 1988. *Can. Data Rep. Hydrogr. Ocean. Sci.* No. 110: iv + 226 p.

O'Brien, W. J., H. I. Browman and B. I. Evans. 1990. Search strategies in foraging animals. *Am. Sci.* 78: 152-160.

Ortner, P. B. 1993. Integration of video imaging with optical plankton counting: "Smart-sampling." *U.S. GLOBEC News* 5:9-11.

Osborn, T. R. 1996. The role of turbulent diffusion for copepods with feeding currents. *J. Plankton Res.* 18: 185-195.

Price, J. F., E. A. Terray and R. A. Weller. 1987. Upper ocean dynamics. *Rev. Geophys.* 25: 193-203.

Rothschild, B. J. 1992. Application of stochastic geometry to problems in plankton ecology. *Phil. Trans. R. Soc. Lond. B.* 336: 225-237.

Rothschild, B. J. and T. R. Osborn. 1988. Small-scale turbulence and plankton contact rates. *J. Plankton Res.* 10: 465-474.

Saiz, E. and M. Alcarez. 1992. Free-swimming behavior of *Acartia clausii* (Copepoda: Calanoida) under turbulent water movement. *Mar. Ecol. Progr. Ser.* 80: 229-236.

Saiz., E. and T. Kiorboe. 1995. Predatory and suspension feeding of the copepod *Acartia tonsa* in turbulent environments. *Mar. Ecol. Progr. Ser.* 122: 147-158.

Shimeta, J., P. A. Jumars and E. J. Lessard. 1995. Influence of turbulence on suspension feeding by planktonic protozoa: experiments in laminar shear fields. *Limnol. Oceanogr.* 40: 845-859.

Squires, K. D. and H. Yamazaki. 1995. Preferential concentration of marine particles in isotropic turbulence. *Deep-Sea Res.* 42: 1989-2004.

Sundby, S. and P. Fossum. 1990. Feeding condition of Arcto-Norwegian cod larvae compared with the Rothschild-Osborn theory on small-scale turbulence and plankton contact rates. *J. Plankton Res.* 12: 1153-1162.

Sundby, S., B. Ellertsen and P. Fossum. 1994. Encounter rates between first-feeding cod larvae and their prey during moderate to strong turbulent mixing. *ICES Mar. Sci. Symp.* 198: 393-405.

Thorpe, S.A. 1987. Transitional phenomena and the development of turbulence in stratified fluids: A review. *J. Geophys. Res.* 92: 5231-5248.

Tiselius, P., G. Nielsen and T. G. Nielsen. 1994. Microscale patchiness of plankton within a sharp pycnocline. *J. Plankton Res.* 16: 543-554.

Werner, F. E., R. I. Perry, R. G. Lough and C. E. Naimie. 1996. Trophodynamics and advective influences on Georges Bank larval cod and haddock. *Deep-Sea Res. II*, 43: 1793-1822.

Wishner, K. F., J. R. Schoenherr, R. Beardsley and C. Chen. 1995. Abundance, distribution and population structure of the copepod *Calanus finmarchicus* in a springtime right whale feeding area in the southwestern Gulf of Maine. *Cont. Shelf Res.* 15: 475-507.

Yamazaki, H. 1993. Lagrangian study of planktonic organisms: perspectives. *Bull. Mar. Sci.* 53: 265-278.

Yamazaki, H., T. R. Osborn and K. D. Squires. 1991. Direct numerical simulation of planktonic contact in turbulent flow. *J. Plankton Res.* 13: 629-643.

Yoshida, J. and N. S. Oakey. 1996. Characterization of vertical mixing at a front on Georges Bank. *Deep-Sea Res. II*, 43:1713-1744.

Cycling of Carbon and Nitrogen in the Gulf of Maine

David W. Townsend
University of Maine

Abstract

The Gulf of Maine is a continental shelf sea situated between Cape Cod, Massachusetts, and southwestern Nova Scotia. Its offshore boundary, for the purposes of this discussion, is the northern edge of Georges Bank. Because the history of oceanographic research in the Gulf is quite rich in comparison with other coastal areas around the world, as evidenced by the various papers and reports in this volume, there are at least some data and information available such that an attempt to describe the more important and interesting processes involved in the cycling of carbon and nitrogen might be a productive exercise, insofar as it could reveal gaps in our understanding and identify new avenues of research. That is the purpose of this brief overview. The approach taken is to examine the various fluxes of nitrogen into and out of the Gulf of Maine as they are controlled by advective exchanges with waters outside the Gulf, by atmospheric deposition, and by riverine fluxes, and then to examine how carbon and nitrogen are cycled internally in the Gulf on various time and space scales. The analysis shows that Slope Water that enters the Gulf through the Northeast Channel, and Scotian Shelf Water that enters at the surface, dominate the flux of nitrogen to surface waters. After subtracting loss terms associated with waters exiting the Gulf and losses attributable to internal denitrification, the net nitrogen flux accounts for about 54 gC m^{-2} yr^{-1} of new primary production, which would be available for export by way of higher trophic level species (e.g., fisheries, various migratory species, etc.). A box model is developed that examines vertical nitrogen fluxes, and reveals that the flux of nitrogen into surface waters is sufficient to explain only about 19% of the total primary production of 290 gC m^{-2} yr^{-1}. This means that the Gulf-wide f-ratio (of "new" NO_3-based production to the total production based on both new NO_3 and recycled NH_4) is 0.19, which is more typical of oligotrophic oceans. The expected f-ratio for the Gulf of Maine is nearer to 0.5, which would require an additional flux of new NO_3 to the Gulf equal to about 61% of the total flux already accounted for by all sources: Slope Water, Scotian Shelf Water, rivers and atmospheric deposition. This additional supply of "new" nitrogen is argued to be the result of water column nitrification in Maine Intermediate Water over the course of a year, which underscores the importance of vertical mixing between surface and intermediate waters. The box model also shows that nutrients delivered to surface waters of the Gulf by Scotian Shelf Water is roughly equal to that of Slope Water. It is concluded that better estimates are needed of water flows into and out of the Gulf, along with more measurements of their nutrient loads, and that measurements should be made of water column nitrification rates. An overall conclusion is that vertical mixing processes that deliver nutrients to the productive surface waters drive biological production in the Gulf of Maine, and that construction of carbon and nitrogen budgets that consider only fluxes in and out of the Gulf, and not internal recycling, will be in error.

Background

A number of shoals and banks effectively isolate the Gulf of Maine from the North Atlantic Ocean (Figure 1, next page); the most prominent of these barriers is Georges Bank. At depths exceeding 100 m, the exchange of waters, and the materials they carry, between the Gulf and the North Atlantic is confined to the Northeast Channel between Georges Bank and Browns Bank. Within the interior of the Gulf are three major deep basins: Georges, Jordan, and Wilkinson, which are

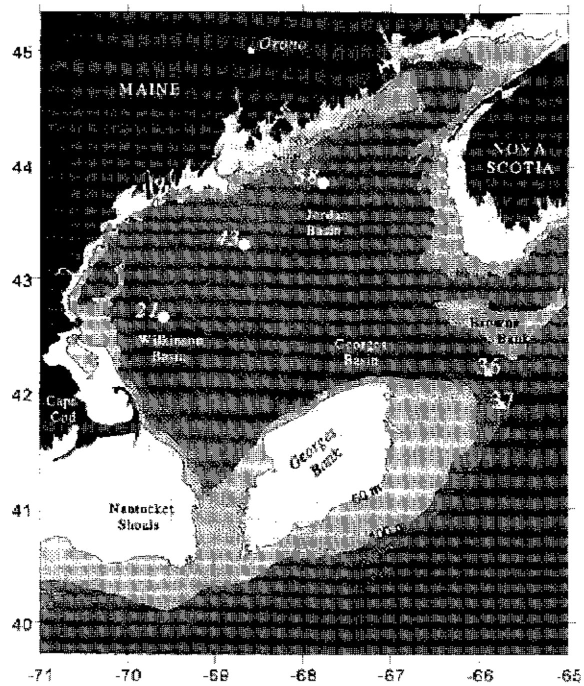


Figure 1. Map of the Gulf of Maine, with features referred to in the text. The 60, 100, 200, and 2000m isobaths are indicated, as are the 3 stations (21,43,and 58) referred to in Figures 7 and 10, and the Northeast Channel stations (36 and 37) referred to Figure 6.

relatively isolated one from another below the 200 m isobath. Georges Basin is the deepest of the three (370 m) and is an extension of the Northeast Channel into the Gulf.

These physical characteristics of deep basins and limited deep water exchanges with the Atlantic Ocean, are coupled with other important features and processes that together dominate nitrogen fluxes and carbon cycling in the Gulf. They include: vertical mixing by tides (Garret et al., 1978); seasonal extremes in heat fluxes, which lead to winter convection and vertical stratification in summer; pressure gradients from the density contrasts set up by Slope Water inflows and river runoff (Brooks, 1985; Pettigrew et al., 1996a); and influxes of the cold, but fresher waters associated with Scotian Shelf Water (Smith, 1983). The result of all these processes is believed to be a fairly productive marine ecosystem in terms of nitrogen fluxes and organic carbon production.

Productivity of the Gulf's inshore areas and offshore banks is well known (Bigelow, 1926, 1927; Bigelow et al., 1940). Levels of primary production in offshore waters, the least productive areas in the Gulf of Maine, average about 290 gC m^{-2} yr^{-1} (O'Reilly and Busch, 1984; O'Reilly et al., 1987). The principal source of nutrients that support this primary production is believed to be the influx into the Gulf of nutrient-rich deep Slope Water (SLW) through the Northeast Channel (Ramp et al., 1985; Schlitz and Cohen, 1984; Townsend 1991). Once delivered into the Gulf, the high concentrations of inorganic nutrients that accompany these deep water intrusions are delivered upward to the surface by various mechanisms and thus are made available for planktonic primary production. Townsend (1991) has reviewed the major nutrient flux mechanisms in the Gulf and discussed three important pathways that deliver new nitrogen to the surface: (1) vertical mixing by tides and upwelling in the eastern Gulf and on the Scotian Shelf, (2) vertical fluxes across the seasonal pycnocline, and (3) winter convection, which supplies the standing stock of nutrients that fuels the spring phytoplankton bloom.

Our knowledge of upwelling of new nitrogen off the Scotian Shelf and off the eastern Maine coast is based on previous work in which we have some confidence (Denman and Herman, 1978; Townsend et al., 1987; Brooks and Townsend, 1989), but very little is known about levels of primary production that result from the nutrient fluxes driven by either winter convection (which precedes the spring phytoplankton bloom) or from vertical mixing across the seasonal pycnocline at other times of the year. Ongoing research is presently directed at the possible role that internal waves might have in promoting vertical nutrient fluxes during the stratified season (Townsend et al., 1996). It is becoming apparent that internal waves may promote vertical nutrient fluxes by way of direct mixing across the pycnocline (Townsend et al., 1996) as well as by vertically oscillating populations of phytoplankton and nutricline waters through an exponentially decaying lightfield (Pettigrew et al., 1996b). Pettigrew et al. (1996b) showed that, theoretically, the later process could enhance specific primary production rates by as much 65% above measured rates during the stratified season in the offshore Gulf. This additional primary production would be "new" primary production (e.g., Dugdale and Goering, 1967) rather than "recycled" production, which normally dominates in stratified waters. Of the three vertical flux mechanisms identified winter convection may be the most important because of the potential importance of the spring bloom in these waters (Townsend and Cammen, 1988; Townsend et al., 1994). To date, however, there have been no organized studies focused on Gulf-wide spring bloom phenomena.

Approach

In order to lay the basis for a discussion of the carbon and nitrogen cycles in the Gulf of Maine, we need to expand our focus beyond our preliminary list of processes that influence the levels of planktonic primary production (such as fluxes of nutrients into the Gulf, and their subsequent vertical mixing), to consider the possible importance of other external sources of carbon and nitrogen, including atmospheric and riverine fluxes, and to examine how these elements are cycled internally in the Gulf on various time and space scales. This approach gets complicated fast, and in order to make sense of it all we might first pose several questions to guide our thinking, and then lay out certain conditions or bounds for our analysis. Among the questions we should keep in mind are:

1. What is an appropriate physical, biological and chemical setting within which to evaluate the carbon and nitrogen cycles?
2. What aspects of these cycles do we already know fairly well?
3. What important aspects remain unknown?
4. Which of these unknown aspects are the most important and should be pursued in the future?
5. Which of these aspects in number 4 are even tractable?

Relevance of Scales and Frame of Reference

In setting relevant bounds for this exercise, it is important to assess first the significance of smaller spatial scales. In particular, we might ask: How important are our estuaries and nearshore environments? Townsend (1991) estimated the rate of new primary production in the Gulf of Maine's estuaries to be ca. 8.3 x 10^{11} gC yr^{-1}. Averaged over the entire area of the Gulf of Maine (1.03 x 10^{11} m^2) in order to assess the contribution of estuaries, this estimate gives a primary production rate of only ca. 8 gC m^{-2} yr^{-1}. Given that the average rate of planktonic primary production in the Gulf of Maine is on the order of 290 gC m^{-2} yr^{-1} (O'Reilly and Busch, 1984; O'Reilly et al., 1987), we must conclude that *for the purposes of evaluating the cycling of carbon and nitrogen in the Gulf of Maine proper*, we can ignore estuaries and inshore areas.

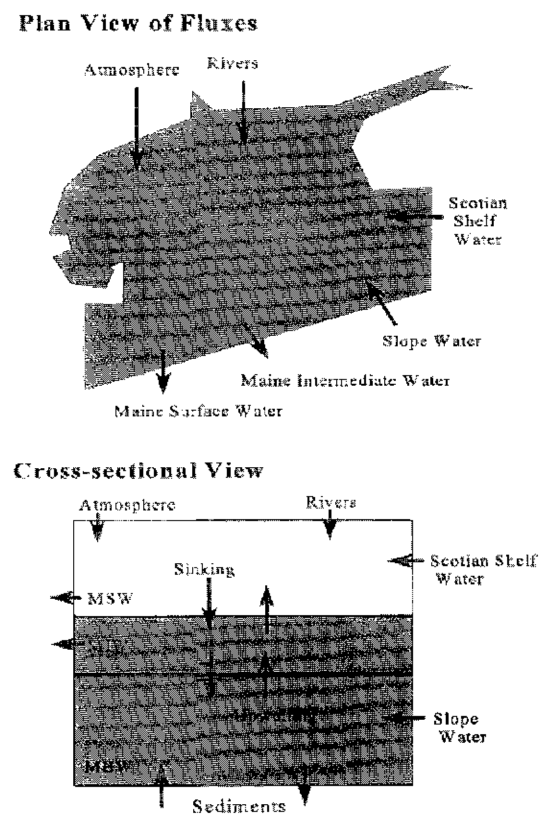


Figure 2. Plan and cross-sectional views of important fluxes of water and its accompanying materials in the Gulf of Maine. This forms the basic conceptual framework for examining total nitrogen entering the Gulf, and total nitrogen exiting the Gulf, as a first step in studying the internal cycling of carbon and nitrogen. MSW=Maine Surface Water; MIW= Maine Intermediate Water; MBW=Maine Bottom Water (Hopkins and Garfield, 1979).

Given these restrictions on our analysis we can adopt a simple view of the Gulf of Maine as shown in Figure 2, whereby we consider first the major fluxes of water that carry loads of carbon and nitrogen (as well as direct atmospheric fluxes), and then examine in more detail the internal cycling processes. Our overall goal in this exercise is to examine the various important storage parameters and the rates associated with each of the flows between them.

Fluxes of water into and out of the Gulf of Maine, as diagramed in Figure 2, are summarized in Table 1 (next page). We see that the major fluxes are associated with the inputs from Scotian Shelf Water, which is a low salinity, cold water mass that enters the Gulf at the surface around southwestern Nova Scotia (Smith, 1983), and deep Slope Water that enters the Gulf along the bottom through the Northeast Channel (Hopkins and Garfield, 1979). The major outputs are associated with Maine Intermediate Water and Maine Surface Water (Hopkins and Garfield, 1979).

These major water masses will carry nitrogen into and out of the Gulf of Maine and thus impart control over the production of organic carbon, which we discuss here by treating the cycling of carbon and nitrogen together. This is diagramed schematically in Figure 3, which includes the more important aspects of the internal cycling of carbon and nitrogen. Accepting this approach, as illustrated in Figures 2 and 3, we can proceed to assign some values to the important fluxes and storages, and thus evaluate our understanding of the carbon and nitrogen cycles in the Gulf of Maine.

Table 1.
Water budget for the Gulf of Maine (modified from Christensen et al., 1995; additional data from Ramp et al., 1985; Schlitz and Cohen, 1984; McAdie, 1994). Evaporation is assumed to equal precipitation plus river inputs (which may not be true); MIW = Maine Intermediate Water; MSW = Maine Surface Water (Hopkins and Garfield, 1979). MSW and MIW output volumes assume that MSW extends from the surface to 25m depth, MIW extends from 25m to 75 m depth, and that the sum of these two volumes equals Northeast Channel and Scotian Shelf Water inputs.

Process	Volume (10^{12} m^3 yr^{-1})
Inputs	
Northeast Channel	8.7
Scotian Shelf Water	6.31
Rivers	0.08
Precipitation	0.08
Outputs	
MSW	5.04
MIW	10.06
Evaporation	0.16

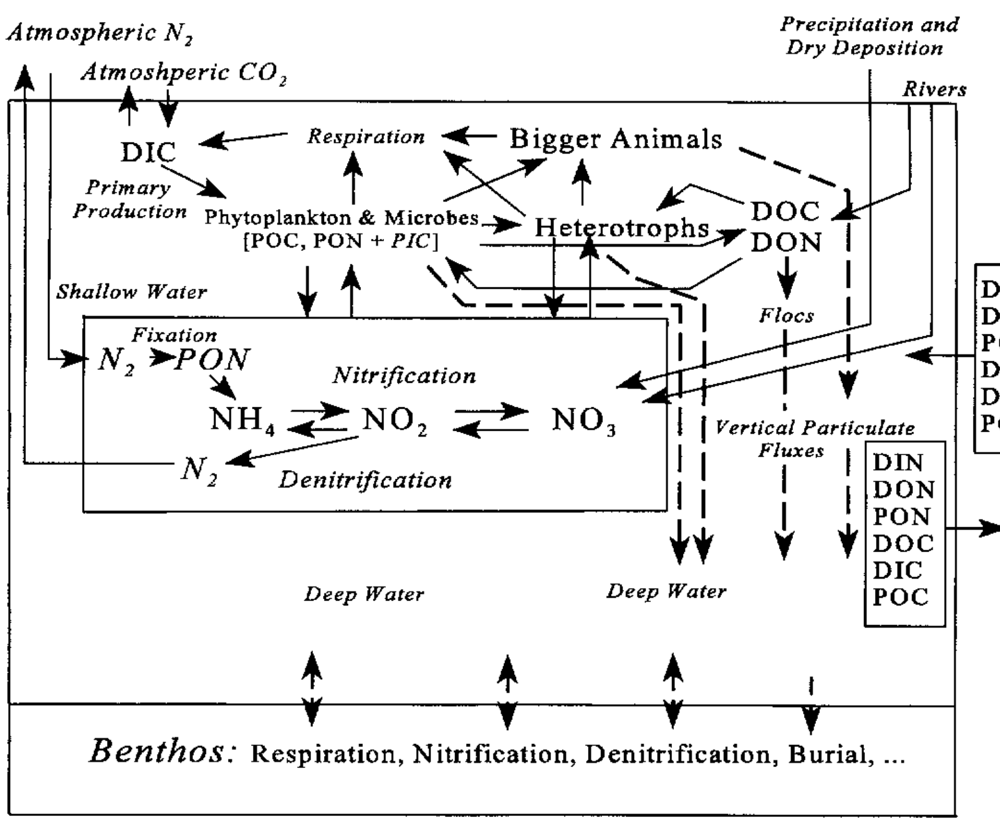


Figure 3. Schematic diagram of the more important processes involved in the internal cycling of carbon and ntirogen in the Gulf of Maine. DIN=dissolved inorganic nitrogen; DON=dissolved organic nitrogen; PON=particulate organic nitrogen; DIC= dissolved inorganic carbon; DOC=dissolved organic carbon; POC=particulate organic carbon. Vertical particle fluxes are indicated by the dashed arrows. Arrows into and out of the side of the box indicate water mass fluxes associated with MSW (Maine Surface Water), MIW (Maine Intermediate Water), and SW (Slope Water).

Carbon Cycling

Primary and Secondary Production of Organic Carbon

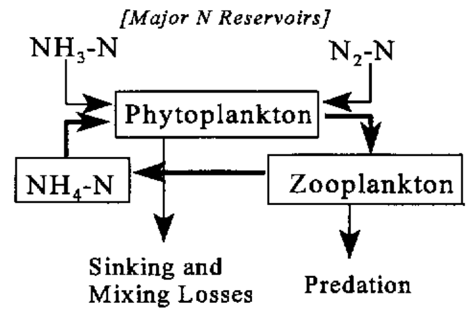
As already mentioned, the estimated level of planktonic primary production in the Gulf of Maine is about 290 gC m^{-2} yr^{-1} (O'Reilly and Busch, 1984; O'Reilly et al., 1987). The portions of that primary production that are channeled into higher trophic levels (shown in Figure 3 as heterotrophs and bigger animals) are given in terms of secondary production, as estimated by Cohen and Grosslein (1987) based on many assumptions; their estimates, presented as percentages of primary production, are:

Macrozooplankton	8.06%
Microzooplankton	14.31%
Macrobenthos	3.82%
Fish (total)	1.24%

There have been few, if any, detailed published accounts of zooplankton grazing and production in the Gulf of Maine, and there is certainly room for more work on the relationship between primary and secondary production, especially given the apparent efficiency with which this trophic transfer operates as compared with Georges Bank. That is, primary production on the shallow Georges Bank is much higher than that of the Gulf of Maine (400 gC m^{-2} y^{-1} in the central portion of Georges Bank, versus 290 gC m^{-2} y^{-1} , O'Reilly et al., 1987), but the ratio of secondary production of zooplankton and benthos to primary production by phytoplankton on the Bank is lower than that in the Gulf (Cohen and Grosslein, 1987; Sherman et al., 1987). Total secondary production on Georges Bank has been estimated at 18% of phytoplankton production, while in waters of the adjacent Gulf of Maine we see from the figures above that it totals 26% (Cohen and Grosslein, 1987). Part of the reason for this difference is believed to result from more severe nutrient limitation of secondary production on the shallow Bank, where new nutrients must enter from around the Bank edges, than in the much deeper Gulf, where vertical fluxes dominate; this is discussed more fully in Townsend and Pettigrew (1997).

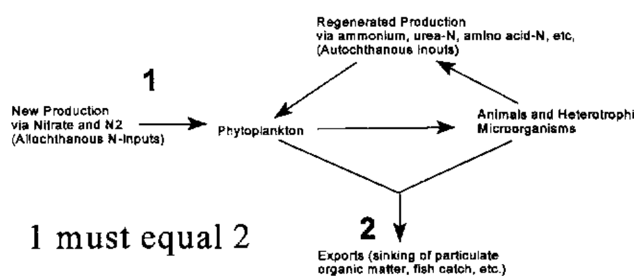
The relationship between primary production and secondary production is not as simple as it might at first appear, and as was pointed out by Dugdale and Goering (1967),

> " ... measurement of primary production alone is not enough to assess the capacity of a region to support production at higher trophic levels in the food chain".



The reason is shown diagrammatically here (modified from Dugdale and Goering, 1967): they pointed out that, in theory, ammonia can cycle indefinitely, if the phytoplankton incur no losses whatsoever to zooplankton grazing or sinking. Under such conditions the phytoplankton would just keep fixing organic carbon and completely recycle the nitrogen forever (as shown by the bold loop). Thus, only by phytoplankton taking up nitrate, or nitrogen that is "new" to the system from external reservoirs, could there be any possibility of "export" production to either higher trophic levels, or for vertical flux to deep water reservoirs or burial in the sediments. Produc-tion that results from the uptake of nitrate is termed "new production", while that from the uptake of ammonium is termed "recycled production".

Eppley and Peterson (1979) followed up with Dugdale and Goering's work and placed it all in a global primary production and carbon cycling scheme.



They argued that in order for the system to not run down, the nutrients lost by exports must be replaced by external inputs, e.g., by the injection of nutrients from deep water into the euphotic zone (or other sources, such as atmospheric inputs). They thus defined the f-ratio, which is the ratio of nitrate uptake by phytoplankton to the uptake of both nitrate and ammonium, e.g.,

$$f = \frac{[NO_3]}{[NO_3]+[NH_4]}$$

For oligotrophic open ocean waters the f-ratio is generally on the order of 0.1, meaning that only ca. 10% of the primary production is "new" production, and the remainder (90%) is "recycled" production dependent on ammonia. More productive systems like the Gulf of Maine would likely have an *f*-ratio on the order of 0.5.

Coming back to our discussion of the Gulf of Maine and Georges Bank, it appears that the proportion of "new" primary production to total primary production is greater in the Gulf than on Georges Bank. Higher rates of new primary production, as occurs in the Gulf, allow for greater secondary production. The resulting difference in secondary production between these two marine systems is revealed in the temporal and spatial patterns of annual zooplankton abundance in each area. For example, the annual cycle of copepods on Georges Bank exhibits a mid-spring peak, which follows the spring phytoplankton bloom, and then it abruptly declines to low summertime levels; this is in sharp contrast to the Gulf of Maine, where the decline in summer is far more gradual (Sherman et al., 1987). That is, zooplankton production on Georges Bank is unusually low in summer, and may be limited by the low post-bloom nitrogen concentrations, and flux rates, over most of the Bank's area. Despite the high rates of photosynthetic carbon fixation (O'Reilly et al., 1987), the low percentage of new-to-total primary production means that this is mostly recycled primary production on the Bank, and thus nitrogen-containing phytoplankton are unavailable for the production of new biomass at the next trophic level, lest the system run down completely for lack of nitrogen altogether.

Vertical Particulate Fluxes of Carbon and Nitrogen

Vertical fluxes of particulate carbon and nitrogen in the Gulf, depicted by the dashed arrows in Figure 1, are the subject of a study by C. Pilskaln of the University of Maine (Pilskaln et al., 1996), which was still ongoing at the time of this writing. Pilskaln's study is based on sediment traps deployed at 150 and 250m in both Wilkinson Basin and Jordan Basin; the samples are collected at bi-weekly intervals. She is finding that there are strong seasonal signals in particulate organic carbon (POC) flux with maxima in spring and fall. There are also indications of very strong resuspension of benthic material in both basins as revealed by the 250m trap samples. Flux rates of POC were on the order of 28 mg C m^{-2} d^{-1} at 150m in Wilkinson Basin during the spring bloom period in April 1995, and reached as high as ca. 50 mg C m^{-2} d^{-1} in October. No springtime data were available for Jordan Basin; the October peak reached ca. 40 mg C m^{-2} d^{-1} at 150m. The C:N ratios of the total fluxes are generally close to the Redfield ratio, meaning that there is a significant downward flux of particulate organic nitrogen. Fluxes of particulate inorganic carbon also showed seasonal trends, with maxima in spring and fall, and a weaker peak in summer; the fluxes are generally 10-20% of the POC rates. Pilskaln's data are preliminary, and more detailed analyses and interpretation will await the completion of her study.

Role of the Spring Phytoplankton Bloom

The spring phytoplankton bloom may be a dominant phenomenon in the Gulf of Maine in terms of particulate organic matter flux out of the surface waters — if the Gulf behaves at all like other continental shelf systems. For example, Smetacek et al. (1978) showed that as much as half of the total annual input of organic matter to the benthos in shelf waters may be the result of the spring bloom. Townsend and Cammen (1988) took that argument further and argued that the spring bloom in the Gulf of Maine could significantly enhance benthic production in years when the bloom begins at especially cold water temperatures, and that juvenile demersal fish recruitment could thus be enhanced.

The stage becomes set for the spring phytoplankton bloom in the Gulf of Maine following the winter period of intense vertical mixing that creates surface nitrate levels on the order of 7-10 μM NO_3 (Townsend et al., 1987). Conditions for the initiation and evolution of the spring phytoplankton bloom in the Gulf may conform to one of two scenarios: (1) it may be set up according to the classical Sverdrup (1953) model, whereby a thermocline develops in spring creating a shoaling upper mixed layer, which, in conjunction with deepening light penetration in spring, reaches a critical light intensity in the upper layer and net planktonic production commences. Riley (1957; 1967) suggested that the value of the critical light intensity that triggers the bloom is reached when the depth averaged, vertically integrated solar irradiance within the mixed layer increases to ca. 40 Ly d^{-1} (20.9 W m^{-2}); this has been corroborated by a number of subsequent reports (Gieskes and Kray, 1975; Pingree et al., 1976; Hitchcock and

Smayda, 1977; and others). (2) In a more interesting and potentially important scenario, it has been shown that the spring bloom may develop in the absence of any vertical water column stability at all (Townsend et al., 1992, 1994). That is, we find that the spring bloom can begin following the winter period of convective mixing, and prior to the vernal development of vertical water column stability, provided that wind speeds (for vertical mixing) are below a certain, predictable threshold, which in the Gulf of Maine, is about 20 kts (Townsend et al., 1994). In such cases, phytoplankton bloom production may not exhaust the supply of nutrients prior to the development of the seasonal thermocline. Instead, there may be several spring bloom pulses, each interrupted by self-shading light limitation or vertical wind mixing events. Eventually the seasonal thermocline develops and nutrient exhaustion curtails bloom production. This possibility of a succession of episodic blooms means that the spring bloom may be significantly more productive, result in more export production, and be more important to the carbon and nitrogen cycles, than has been previously assumed.

The Inorganic Carbon System

Major unknowns with respect to the carbon cycle involve the inorganic carbon system, for which there are virtually no measurements for the Gulf of Maine. The same is true for our understanding of dissolved organic carbon — its production, fate and cycling within the system. The inorganic carbon system is depicted very simply in Figure 1 as DIC and PIC (for dissolved and particulate inorganic carbon). Ongoing research in this area includes that of Grazianno et al. (1996) who are presently measuring rates of particulate organic and inorganic (calcite) production in the Gulf of Maine. Their preliminary data suggest that particulate inorganic carbon production rates in summer in the offshore waters of the Gulf are on the order of 10-20% of organic carbon production, which is in keeping with Pilskaln's flux measurements. Lack of additional studies concerning the inorganic carbon system in the Gulf of Maine is unfortunate given the recognition of the possible importance of continental shelf seas in the global carbon cycle (Kempe, 1995). The measurements are relatively simple to make and additional information can be gleaned from empirical relationships between pCO_2 and pH, as shown in Figure 4 for the North Sea (Kempe, 1995). Data collected in the North Sea show that parts of it have pCO_2 levels that exceed that of the atmosphere (ca. 350 ppmv), meaning that it is a source of CO_2 to the atmosphere, and while other parts show the opposite trend (Kempe, 1995). Excess pCO_2 over atmospheric levels would indicate that those waters are behaving heterotrophically, respiring more organic carbon that is being fixed, and implying that those waters receive organic matter of allochthonous origin (i.e., from rivers). It is important to note that the relative proportion of new to recycled primary production, as discussed earlier, is irrelevant with

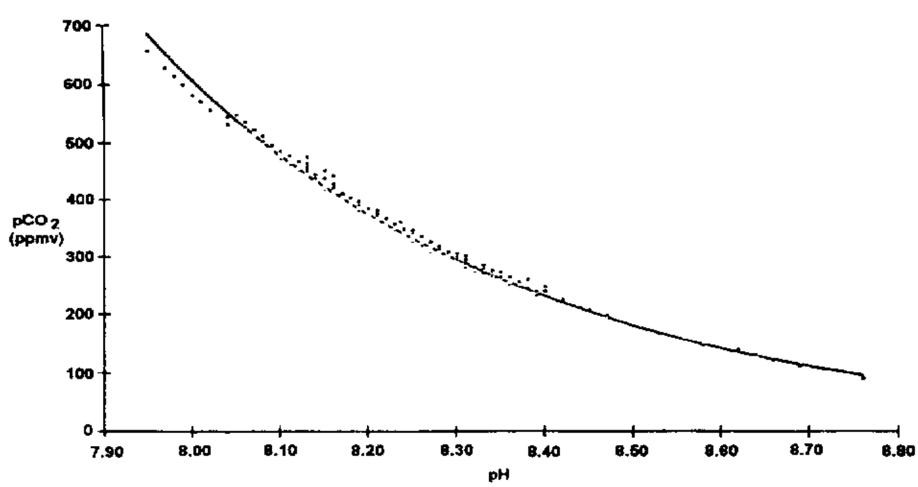


Figure 11. Relationship between pCO_2 and pH in the North Sea during May/June 1986 ($pCO_2 = 158.86 \times 10^9 \times e^{(-2.4420 \times pH)}$: Kempe and Pegler, 1991).

Figure 4. From Kempe (1995).

respect to surface water CO_2 drawdown by phytoplankton carbon fixation; on short time scales it depends only on CO_2 fixation.

Nitrogen Cycling

There are many more data sources and published accounts of nitrogen (and other plant nutrients) in the Gulf of Maine than there exists for inorganic carbon. The first nitrogen budget was published by Schlitz and Cohen (1984), which underscored the importance of Slope Water fluxes into the Gulf through the Northeast Channel. Based on Schlitz and Cohen's work, Townsend (1991) assessed the major oceanographic processes that affect nitrogen fluxes in the Gulf, as discussed above. Later, Christensen et al. (1995) examined the nitrogen cycle in the Gulf with particular attention to the importance of sediment denitrification. With the major sources and processes indicated in Figures 2 and 3, we can begin to reconstruct yet another nitrogen budget for the Gulf of Maine. Based on our discussion of new and recycled primary production, we should view our new nitrogen budget accordingly. That is, we should examine: (1) the primary production that would result from fluxes of nitrogen into the Gulf of Maine (N_{in}), based on the Redfield Ratio of C:N, (2) losses of potential carbon production as a result of internal denitrification of that initial nitrogen flux once entered ($N_{de\text{-}N}$); and (3) organic carbon equivalents of fluxes of nitrogen out of the Gulf of Maine (N_{out}), where:

$$\textit{Potential Exports} = (N_{into} - N_{de\text{-}N} - N_{out})$$

This will then allow us to estimate potential annual new primary production that would be available for export to fisheries, or other forms of export, such as migratory species. The next step would then be to take the ratio *(R)* of our estimated potential primary production that would result from fluxes of new nitrogen into the surface waters to measurements of total primary production (which includes both new and recycled), as:

$$R = \frac{N\ Flux\ into\ MSW}{290\ gC\ m^{-2}\ yr^{-1}} = \frac{Potential\ New\ PP}{Total\ Measured\ PP} \cong f - ratio$$

This ratio *(R)* is one way to estimate the f–ratio discussed earlier — for the Gulf as a whole over an annual cycle — but it would not account for any internally-recycled nitrogen that occurs by way of nitrification within the Gulf. That is, if any of the new nitrogen that enters the Gulf is remineralized and internally recycled back to nitrate, by way of internal nitrification

Table 2.
River Flows into the Gulf of Maine, by state and province (from McAdie, 1994).

Province/State	Annual Total
Nova Scotia	$0.085 \times 10^{10} \cdot m^3 \cdot yr^{-1}$
New Brunswick	$3.438 \times 10^{10} \cdot m^3 \cdot yr^{-1}$
Maine	$3.302 \times 10^{10} \cdot m^3 \cdot yr^{-1}$
New Hampshire	$0.480 \times 10^{10} \cdot m^3 \cdot yr^{-1}$
Massachusetts	$0.744 \times 10^{10} \cdot m^3 \cdot yr^{-1}$
	Total = $8.049 \times 10^{10} \cdot m^3 \cdot yr^{-1}$

processes, then our calculated f-ratio *(R)* will be an underestimate. Therefore, forcing $R = f$-ratio of ca. 0.5 (or so; Eppley and Peterson, 1979) necessitates our accounting for enough new nitrogen fluxes in the numerator of the above equation for it to equal 0.5. If we come up short — if our computed $R < 0.5$ — then we must concede that either our nitrogen flux estimates are in error, or that there is internal nitrification in the Gulf that "re-creates new nitrate". A tally of input and output fluxes of nitrogen in the Gulf of Maine is given in the following sections.

Riverine Sources of Nitrogen

The volume of river waters entering the Gulf of Maine region are given above in Table 2, which shows that the greatest volume of river water comes from Maine and New Brunswick. Thus, we may take as representative concentrations of both dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON) the values obtained by Mayer et al. (1996) which are on the order of 10 μM nitrogen for three river systems in Maine (the Kennebec, Damariscotta and Sheepscot Rivers). The product of total river flow ($8.049 \times 10^{10} \cdot m^3 \cdot yr^{-1}$) and nitrogen concentration (1×10^{-2} g-at m^{-3}) gives a flux of 1.13×10^{10} g N yr^{-1} into the Gulf.

Atmospheric Deposition of Nitrogen

Atmospheric deposition of nitrogen in the marine environment is receiving a great deal of attention in recent years (Lovett, 1994, Jickels, 1995; Paerl, 1995). On a global scale, the magnitude of the contribution of atmospheric fluxes of nitrogen is comparable with that from rivers, with rivers contributing a flux of between 1500 and 3570 x 10^9 moles N yr^{-1}, and the atmosphere contributing 2140 x 10^9 moles N yr^{-1} (Jickels, 1995).

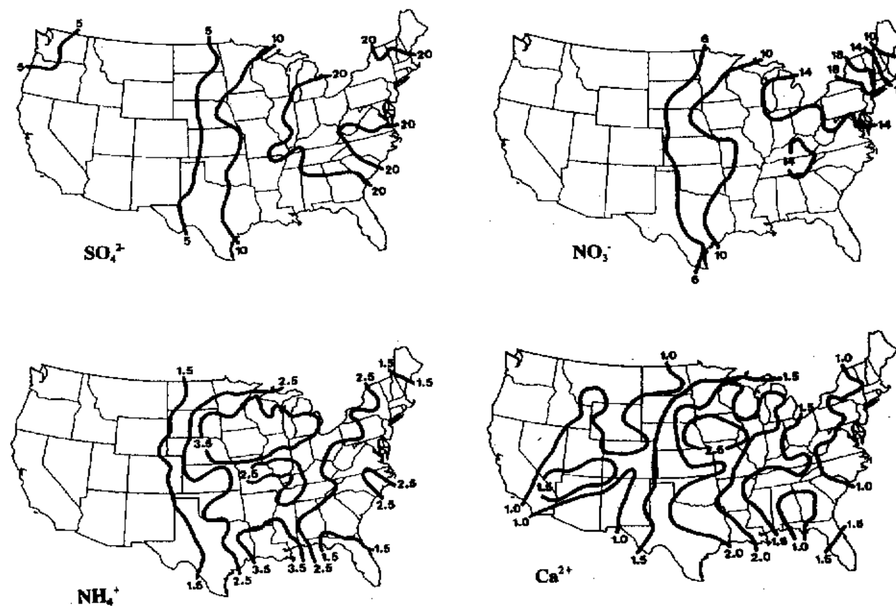


FIG. 5. Patterns of wet deposition (in kilograms per hectare per year) of sulfate, nitrate, ammonium, and calcium in the United States for 1991, as reported by the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) (NADP 1992).

Figure 5. From Lovett (1994).

The fluxes vary with location and proximity to anthropogenic sources, as shown in Figure 5 from Lovett (1994). As can be seen in Figure 5, the atmospheric (wet) deposition of NH_4 and NO_3 to the Gulf of Maine area is on the order of 10 kg NO_3 hectare^{-1} yr^{-1}, and 1.5 kg NH_4 hectare^{-1} yr^{-1}. This is equivalent to 0.0208 moles NO_3-N m^{-2} yr^{-1} and 0.0088 moles NH_4-N m^{-2} yr^{-1}. Lovett's (1994) numbers are the same order of magnitude as those measured by R. Talbot and B. Mosher of the University of New Hampshire in their study of atmospheric deposition in the Gulf of Maine region (e.g., Mosher et al., 1996). They found that the total deposition of nitrogen, including both wet and dry phases of nitrate and ammonia was about 0.09 moles N m^{-2} yr^{-1} in 1994 and 0.04 moles N m^{-2} yr^{-1} in 1995. Nixon et al. (1995) reported that Narragansett Bay receives about 0.091 moles N m^{-2} yr^{-1}. Thus, a value of 0.09 moles N m^{-2} yr^{-1} is taken as representative for this discussion.

Advective Fluxes of Nitrogen

Using the water budget in Table 1, and concentrations of nitrogen in the various water masses in the Gulf of Maine region, the advective fluxes of nitrogen identified in Figure 2 can be evaluated. The water mass with the highest nitrogen concentrations is Slope Water (Schlitz and Cohen, 1984; Ramp et al., 1985) which can be operationally defined as waters with salinity >34 psu. Slope Water is shown in Figure 6 (next page) for two stations sampled in the Northeast Channel in April of 1994. The near-surface waters at both stations are colder and fresher than waters beneath and no doubt reflect a contribution from Scotian Shelf Water. At Station 37, Slope Water is present below a depth of about 150m, while at Station 36, it is present as two forms, beginning below a depth of about 40m. The distinct water mass at Station 36 between 40 and 160m (temperature >9-10°C and salinity >35) is described as Upper Slope Water, or Warm Slope Water (WSW) by Ramp et al. (1985). Beneath the WSW is a bottom water layer of Labrador Slope Water (LSW; Ramp et al., 1985; salinity >35, temperature ca. 8.2°C). The DIN concentrations at depth are noticeably higher at Station 36 than Station 37, and most likely reflect the contribution of higher nutrient concentrations in WSW than LSW at the same depth in the water column. Thus, the question we face is: What concentration of DIN do we ascribe to waters entering the Gulf of Maine through the Northeast Channel? The deep Slope Water has a nitrite+nitrate concentration as high as 21 μM (e.g., at Station 36). Shallower Slope Water DIN concentrations (nitrate+nitrite concentration at 34 psu salinity) are as low as 13 μM (at both Station 36 and 37).

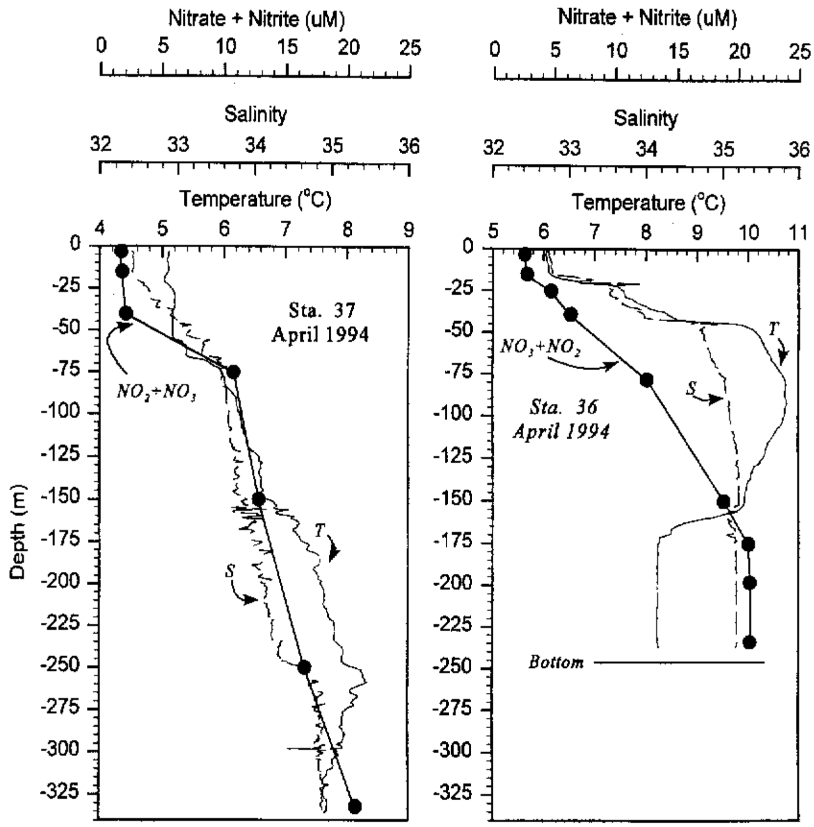


Figure 6. Vertical profiles of temperature, salinity and nitrate+nitrite at two stations in the Northeast Channel (see Figure 1 for locations) in April, 1994 (data from Townsend et al., 1994). Note the distinct warm and salty midwater layer between 40 and 160m at Station 36, which is characteristic of warm Slope Water (e.g., Ramp et al. 1985) and that nitrate+nitrite concentrations are higher in the deeper waters at Station 36.

The estimated nitrogen loads accompanying these outputs of MSW and MIW do not include the dissolved or particulate forms (DON,PON); DON concentrations can be similar to DIN in coastal waters, and an order of magnitude greater than PON (Sharp, 1983). Because I am unaware of data on DON for the Gulf of Maine, I have made the bold assumption that the flux of DON and PON into the Gulf is equal into the flux out; if true, these fluxes cancel out and are therefore not considered. Of course there are numerous data available on DIN concentrations in the Gulf. Annually averaged DIN concentrations are estimated to be 3.5 μM for MSW (which ranges from near 0 μM in summer to ca. 8 μM in winter), and 8 μM in MIW (Townsend and Christensen, 1986; Townsend et al., 1987). These data, and those in the literature cited, produce the approximate advective fluxes into and out of Gulf as given in Table 3.

We see from Table 3 that the bulk of the nitrogen flux into the Gulf of Maine is associated with Slope Water. The influence of this water mass throughout the Gulf of Maine can be seen in Figure 7, which shows the differences in deep water nitrate concentrations as a function of proximity to the Northeast Channel source of Slope Water. The general trend is for deep waters in the western Gulf to have lower concentrations of nitrate.

A linear average would be 17 μM for Slope Water. The other major influx of water and nutrients into the Gulf is via Scotian Shelf Water, which has DIN concentrations on the order of 5 μM (Christensen et al., 1995; P.C. Smith, pers. Comm.).

Fluxes out of the Gulf are associated with Maine Surface Water and Maine Intermediate Water (Hopkins and Garfield, 1979). Because Ramp et al. (1985) estimated Slope Water influxes through the Northeast Channel to be below 75m depth, the outputs of MSW and MIW are assumed in this exercise to be associated with waters from 0-75m depth, with MSW being 0-25m and MIW being between the base of MSW and 75m. The volume flows are computed as simple proportions, with no consideration given to possible variations in flow with depth.

Losses of Nitrogen

In addition to the processes just discussed, whereby we arrive at the figures shown in Table 3, Christensen et al. (1995) have shown that some nitrogen is "lost" through other mechanisms: by the processes of denitrification, burial in the sediments, and other exports (such as that attributable to fisheries landings, migratory fishes, whales and birds, etc.). Christensen et al. showed that as the high

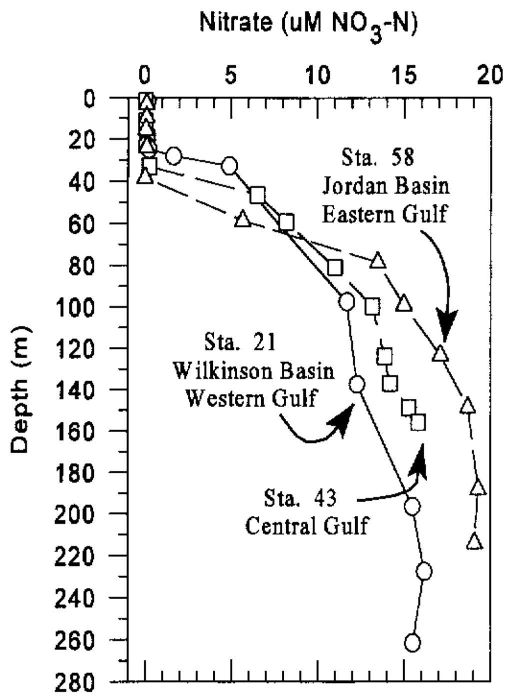


Figure 7. Vertical profiles of nitrate for three stations in the Gulf of Maine, July, 1985 (locations given in Figure 1). Station 58 in Jordan Basin in the eastern Gulf and nearest to the Northeast Channel, Station 21 in Wilkinson Basin in the western Gulf and furthest from the Northeast Channel, and Station 43 intermediate between the two. Data from Townsend and Christensen (1986).

nutrient, deep Slope Waters spread at depth across the Gulf of Maine's basins, there is an apparent loss of DIN from east to west (Figure 7 and Figure 8). For example, the plots in Figure 8 (next page) show that DIN, plotted against phosphate, is depleted in the western Gulf; silicate, on the other hand, does not show this depletion.

The data argue for significant sediment denitrification that acts to remove DIN from the overlying water column; this removal was estimated by Christensen et al. (1995) to be 33.1 x 10^9 g at N yr^{-1}. Losses of nitrogen as a result of burial is given as 5 gC m^{-2} yr^{-1}; with a C:N ratio of 10, this converts to a burial rate for nitrogen of 4.4 x 10^9 g at N yr^{-1} (Christensen, 1989).

The analysis presented in Table 3 shows that there is a net flux of nitrogen into the Gulf of Maine of 54 x 10^9 g at N yr^{-1}. The net flux term divided by the area of the Gulf (1.03 x 10^{11} m^2) gives an area-specific flux rate of 0.52 g N m^2 yr^{-1}. Multiplying by the Redfield Ratio for carbon to nitrogen (5.67 by weight) gives a value of 3 gC m^{-2} yr^{-1} *new net* primary production that is available for transfer to higher trophic levels and subsequent export from the Gulf. This is equal to approximately 300,000 metric tons (MT) of carbon per year for the Gulf of Maine. But how realistic is this estimate of "exportable" production? Cohen and Grosslein (1987) reported a value of 32 kcal/m^2 for fish and squid

Table. 3.

Advective fluxes of nitrogen into and out of the Gulf of Maine based on the water budget in Table 1, and nitrogen concentrations as footnoted. The fluxes are for the area of the Gulf, assumed to equal 1.03 x 10^{11} m^2.

Flux	Volume (10^{12} m^3 yr^{-1})	[N] (μg at N L^{-1})	N Flux yr^{-1} (10^9 g at N yr^{-1})
Inflows:			
Atmosphere (wet and dry)†			9.3
Rivers‡	0.08	10.	0.8
Scotian Shelf Water‡	6.31	5.0	31.5
Slope Water (NE Ch.)‡	8.7	17	147.9
		Total Inflows	189.5
Outflows:			
MSW¥	5.04	3.5	17.6
MIW¥	10.06	8.0	80.5
		Total Outflows	98.1
Other Losses:			
Denitrification¶			33.1
Burial§			4.4
Net Flux			+53.1

†/ From Talbot and Mosher, unpublished; ‡/ Modified from Christensen et al., 1995, and McAdie, 1994; ¥/ From Townsend and Christensen, 1986, and Townsend et al., 1987; ¶/ From Christensen et al., 1995; §/ From Christensen, 1989.

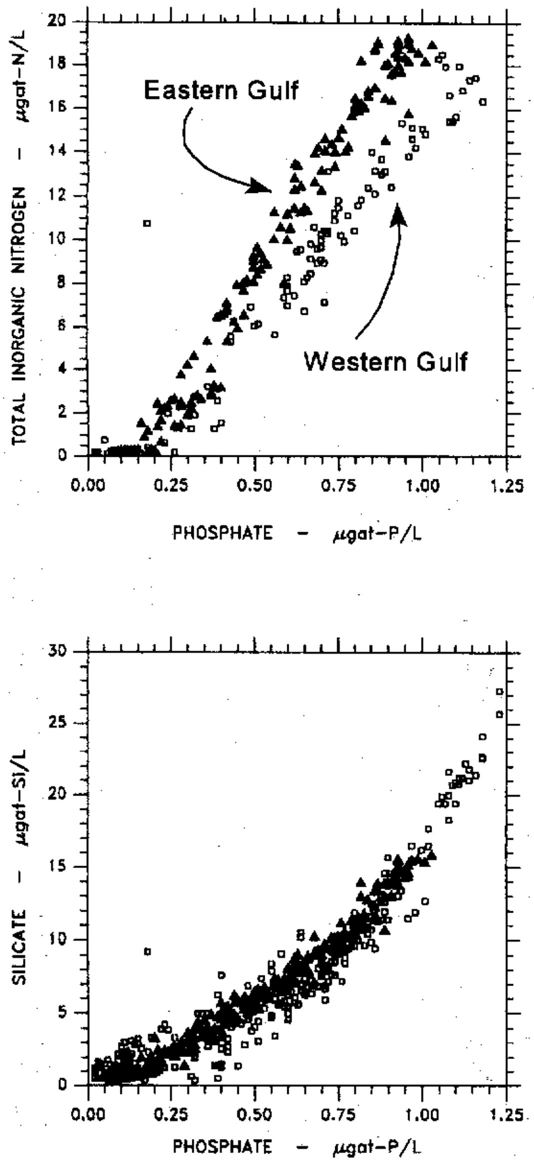


Fig. 4. Relationship between TIN and phosphate (top) and between dissolved silicate and phosphate (bottom) for all samples on transects 2 (open squares) and 9 (filled triangles).

Figure 8. From Christensen et al. (1995). TIN - phosphate (top) and silicate - phosphate relationships below for the eastern and western Gulf of Maine. Open squares are data from the western Gulf.

production in the Gulf of Maine prior to the 1960s; this is converted by assuming 1gC = 11.4 kcal, giving 289,000 MT carbon, which is close to our estimate, and lends some confidence to our calculations and assumptions.

The analyses in Table 3 can be used to construct a box model of nitrogen fluxes among the three water masses and bottom sediments in the Gulf, which is given in Figure 9, and allows us to compare the nitrogen fluxes to measured rates of carbon fixation (primary production). The model shows that once we account for the inputs of DIN to the Gulf, into both Maine Surface Water (by atmospheric deposition, rivers, Scotian Shelf Water and Slope Water) and Maine Bottom Water (by Slope Water), and the outputs via fluxes of MSW and MIW, we arrive at a gross nitrogen flux into the productive surface waters of the Gulf (the MSW box in Figure 9) of 41.6×10^9 g at N yr^{-1} plus a vertical flux of 34.4×10^9 g at N yr^{-1} which totals 76×10^9 g at N yr^{-1}. This equals 0.69 g at N m^{-2} yr^{-1} when averaged for the area of the Gulf (1.03×10^{11} m^2), and multiplying by the atomic weight of 14 for nitrogen, and the Redfield Ratio of 5.68 (by weight), gives 55 gC m^{-2} yr^{-1} of potential *new* primary production. Divided by the total primary production of 290 gC m^2 yr^{-1} gives an f-ratio of only 0.19. We have already argued that the Gulf of Maine should have an f-ratio of ca. 0.5, based on Eppley and Peterson (1979). For this to be the f-ratio, there would need to be a much greater flux of new nitrogen into the Gulf of approximately 187×10^9 g at N yr^{-1}, which is more similar to the gross inflows in Table 3, before exports are subtracted.

There are a couple possible sources of error that could explain this discrepancy between gross nitrogen fluxes into surface waters of the Gulf, as given by our box model, and the expected flux, based on an f-ratio of 0.5 and measured total primary production. One obvious error would be the assumption of an f-ratio of 0.5. Could 0.19 be the actual value? To answer this question would require actual measurements of new and recycled primary production in the Gulf, and to date there have been none. Another source of error could be our flux estimates in Table 3. For example, Ramp et al. (1985) influx of Slope Water of 262×10^3 m^3 s^{-1} has a standard deviation of 199×10^3 m^3 s^{-1}. Their measurements also showed that the residence time of the deeper waters in the Gulf are on the order of 1 year. But if we accept the average fluxes given in Table 3, then we need to provide an additional annual nitrogen flux into surface waters of ca. 115.5 g at N m^{-2} yr^{-1}, which is shown by the dashed box in Figure 9 as the result of nitrification of vertically-settling organic material into Maine Intermediate Water,

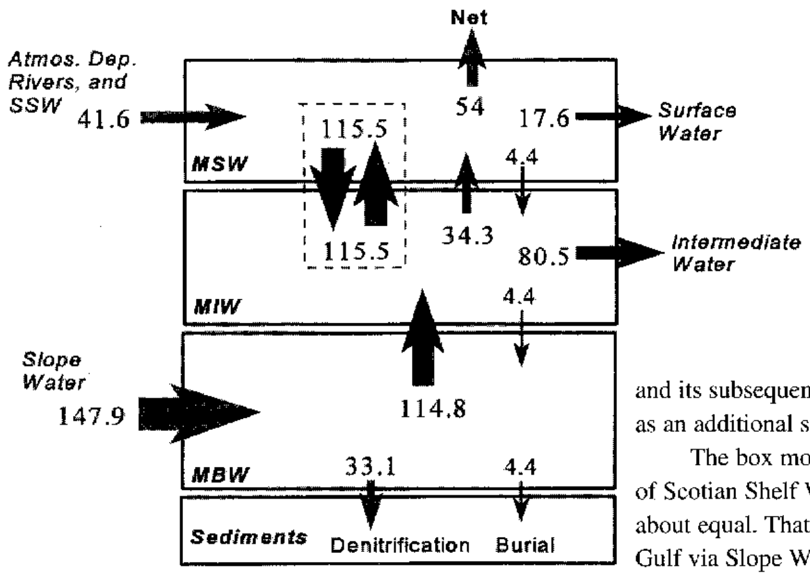


Figure 9. Box model of nitrogen fluxes among the three Gulf of Maine water masses and bottom sediments. Flux units are 10^9 g at N yr^{-1}. The gray arrows are the flux values given in Table 3. The black arrows are the vertical fluxes needed for steady state balance. The black arrows in the dashed box represent the downward flux of organic nitrogen and the equivalent upward flux of nitrate that results from nitrification in the intermediate water layer.

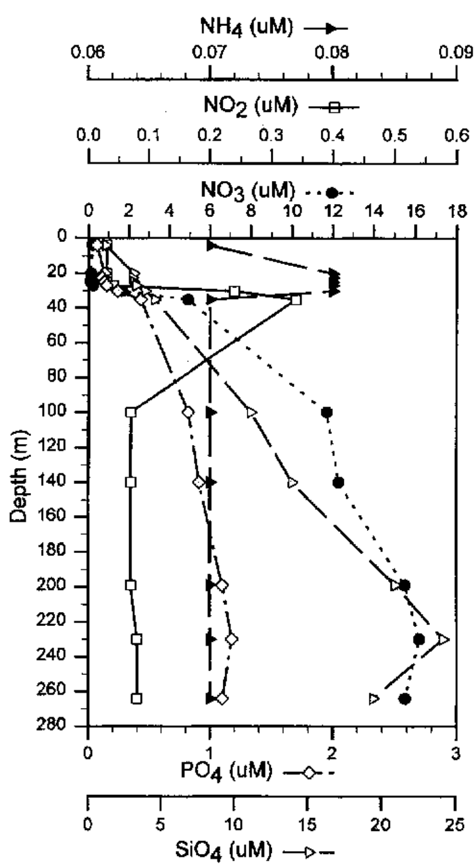


Figure 10. Profiles of ammonia, nitrite, nitrate, phosphate and silicate at Station 21 (see Figure 1) in Wilkinson, collected in July 1985 (data from Townsend and Christensen, 1986). Note the nitrite maximum at 40m, which occurs beneath a slight ammonia maximum.

and its subsequent vertical flux back into surface waters as an additional source of *new* nitrate.

The box model also illuminates the significance of Scotian Shelf Water relative to Slope Water: they are about equal. That is, much of the nutrient flux into the Gulf via Slope Water leaves the Gulf with exiting intermediate waters or is denitrified. Only 23% of the nitrogen that comes in via Slope Water through the Northeast Channel is delivered upward to the surface layer where it becomes available to phytoplankton. Thus, much of the nitrification presumed to occur in intermediate waters, is acting upon as many nitrogen atoms that came in via Scotian Shelf Water as it is on atoms that came in via deep Slope Water.

Nitrification in the Gulf of Maine

Throughout this exercise we have been working with "new" primary production, based on our gross flux estimates of "new" nitrogen into the Gulf of Maine by way of the fluxes listed in Table 3. The problem with this approach is that there is evidence that "new" nitrogen may be "created" within the Gulf itself, and that therefore not all is from external sources. Our box model argues for significant nitrification, whereby regenerated ammonia is oxidized to nitrite and then nitrate, at an annual rate that approximates 61% of the total nitrate (DIN) inflows (=115.5/189.5). Evidence of nitrification in the water column is seen in Figure 10 for the western Gulf of Maine. Particulate organic matter that settles out of the surface waters is processed by heterotrophic activity, producing ammonia, and then nitrite and nitrate (Figure 3). Figure 10 shows a very slight maximum in ammonia concentration at about 20m, which is likely the result of heterotrophic grazer activity at that depth, producing recycled nitrogen from shallow water-produced organic matter. There is also a subsurface maximum in nitrite (NO_2) at about 40m, which is coincident with the beginning of the nitricline, where nitrate (NO_3) increases steadily with increasing depth below that. The nitrite maximum is evidence of nitrification of ammonia at that depth; it is likely that it is detectable because of light limitation of phytoplankton photosynthesis at 40m, thus preventing the uptake of that nitrite by the primary producers.

Our box model analysis in Figure 9 leads us to believe that such nitrification processes are responsible for a remineralization and recycling rate of about 1.5 times per year for each nitrogen atom that enters the surface waters of the Gulf of Maine as new nitrogen from outside (primarily via Slope Water that enters through the Northeast Channel and Scotian Shelf Water).

Data from Rakestraw (1936) show that such a nitrite maximum as seen in Figure 10 is present throughout the Gulf of Maine for much of the year (Figures 11 and 12). The depth of highest concentration of nitrite in Rakestraw's data is similar to that in Figure 10. The highest concentrations appear to be related to the spring and fall seasons, and may be related to a greater vertical flux rate of organic material at those times. The extensive distributions of nitrite seen in Rakestraw's (1936) data would suggest that water column nitrification is an important, but poorly understood process going on in the Gulf of Maine.

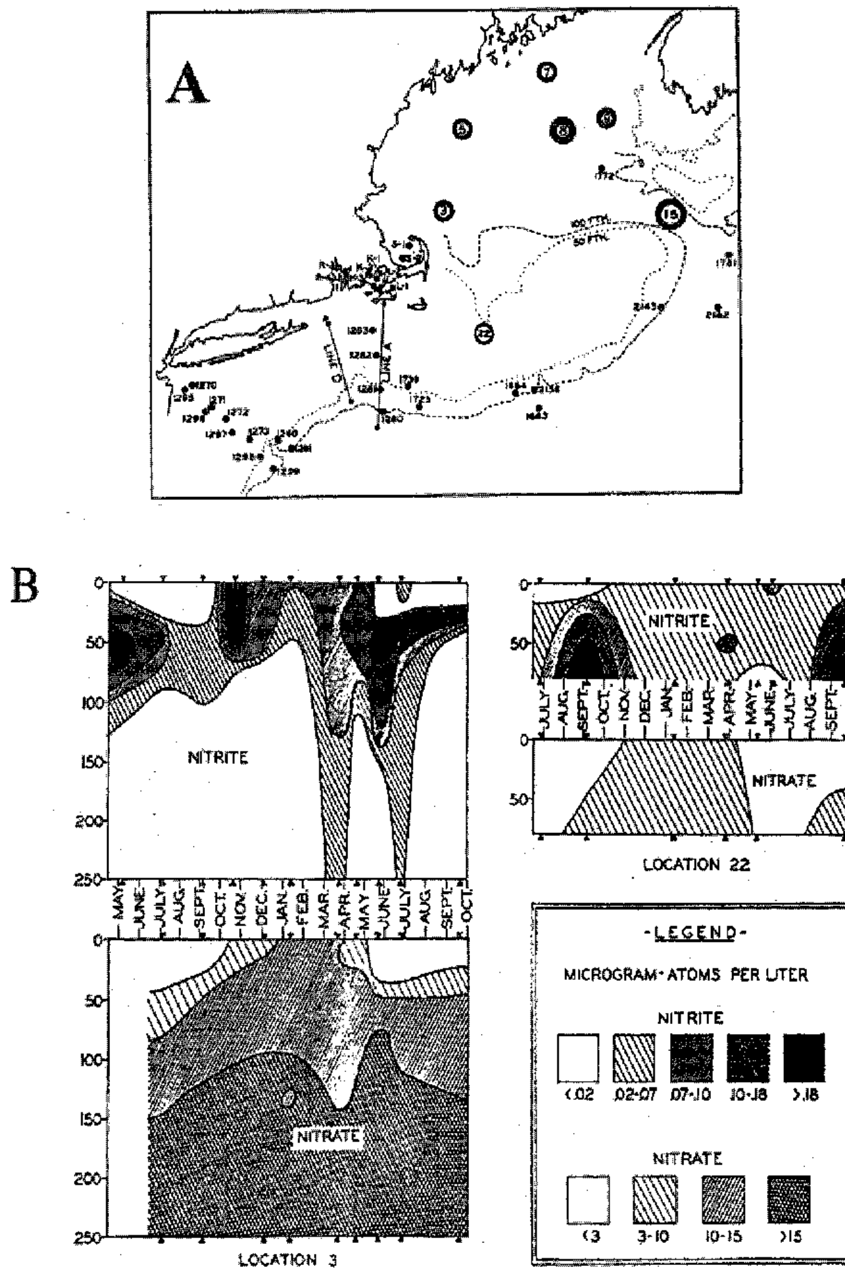


FIG. 5. Seasonal variation of nitrite and nitrate. Locations 3 and 22, Gulf of Maine. Ordinates, depths in meters.

Figure 11. From Rakestraw (1936). Panel A: Locations of sampling stations. Panel B: Contour plots of nitrate and nitrite concentrations over a 1.5 year period for stations in Wilkinson Basin (#3) and in the Great South Channel area of Georges Bank (#22). Concentrations are given in the legend.

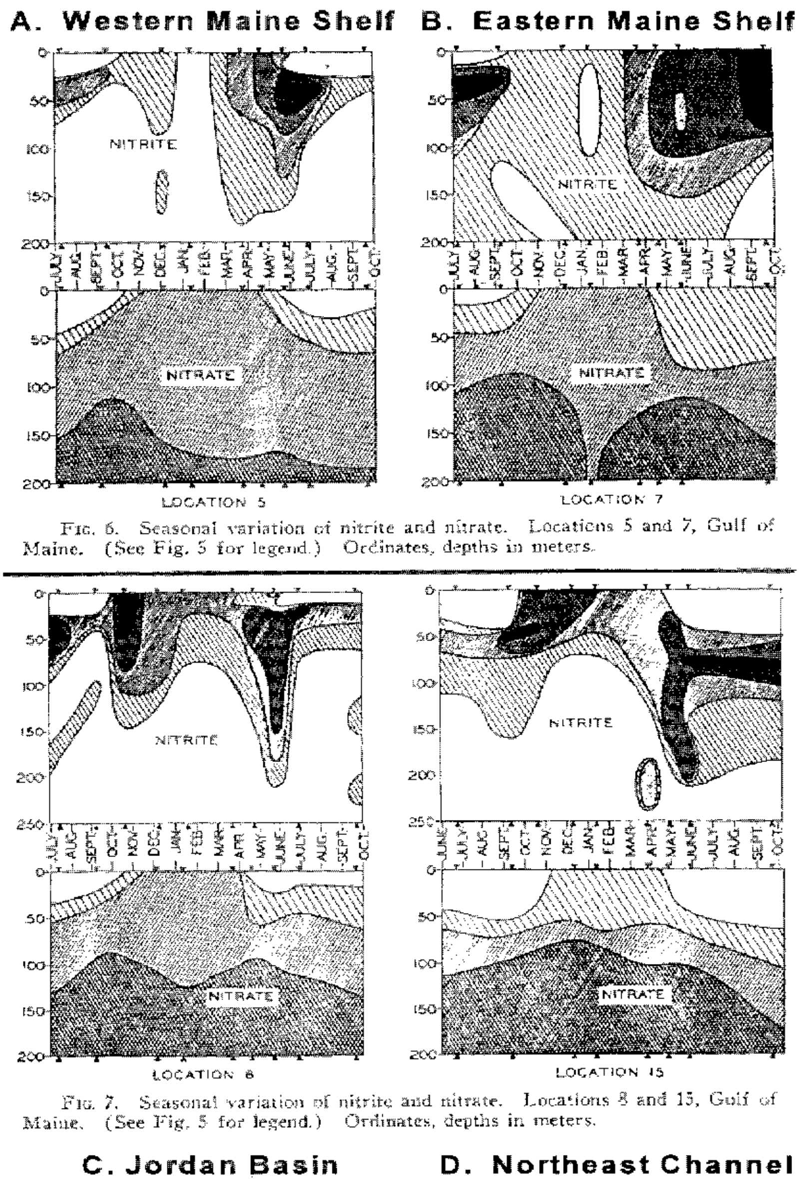


Figure 12. From Rakestraw (1936). Contour plots of nitrite and nitrate at four stations in the Gulf of Maine, shown in Panel A of Figure 11. Legend for concentrations is given in Panel B of Figure 11.

Conclusions

A few conclusions can be drawn from this exercise, beyond those already given in earlier works (e.g., by Schlitz and Cohen, 1984; Ramp et al., 1985; Townsend, 1991; and Christensen et al., 1995). It has become clear that we need better estimates of the advective flows into and out of the Gulf of Maine, along with more detailed measurements of nutrient loads associated with the major flows. Slope Water through the Northeast Channel, and to a lesser extent Scotian Shelf Water, dominate the flux of nitrogen into the Gulf, but even slight errors in either the magnitude of the flows, or the loads of nutrients, or both, can have very large effects on the estimated net nutrient flux. Indeed, the standard error that Ramp et al. (1985) reported for the flow of Slope Water through the Northeast Channel is 69% of the mean. The magnitude of those possible errors will dictate the level of significance we ascribe to rates of water column nitrification in the Gulf. Thus we must also conclude that we need to evaluate much better the significance of nitrification in intermediate waters in the Gulf of Maine by way of actual field measurements. The rate we ascribe in our box model is much greater than other coastal measurements reported by Kaplan (1983) in his review, and is closer to rates reported for Chesapeake Bay. Our box model approach arrived at an estimate only by way of subtraction, and includes all the uncertainties that come with all our flux estimates. Nonetheless, we conclude that nitrification is probably occurring at a rate of 1.5 times per year (115.5/(34.3+41.6); Figure 9) for each nitrogen atom that enters the surface waters of the Gulf from outside, which is attributable primarily to Scotian Shelf Water and Slope Water, in roughly equal proportions. We must face the fact that detailed measurements of advective flows of water and nutrients into the Gulf are only one part of the story, and nitrogen budgets so based could be in large error if internal nitrification is not taken into account.

We can also conclude that nutrients that enter the Gulf of Maine via Scotian Shelf Water are as important as those that enter via the deep Slope Water that comes through the Northeast Channel. Although the gross flux into the Gulf via Slope Water is much greater, only 23% of it reaches the surface layer where it becomes available to phytoplankton (see Figure 9). And herein lies our most interesting conclusion: that vertical mixing processes that deliver nutrients to the productive surface waters drive biological production in the Gulf of Maine. That is, the influx of new nitrogen alone cannot sustain all the observed primary production, because much of that new nitrogen exits the Gulf before being made available to the primary producers. It is the subsurface waters, in the intermediate water layer where we see the primary nitrite maximum, that likely exchanges most energetically with surface waters and provides the nutrients to support the relatively high rates of primary production in the Gulf of Maine.

References

Bigelow, H. B. 1926. Plankton of the offshore waters of the Gulf of Maine. *Bull. U.S. Bur. Fish.* 40: 1- 509.

Bigelow, H. B. 1927. Physical oceanography of the Gulf of Maine. *Bull. U.S. Bur. Fish.* 40: 511-1027.

Bigelow, H. B., L. C. Lillick and M. Sears. 1940. Phytoplankton and planktonic protozoa of the offshore waters of the Gulf of Maine. Part I. Numerical distribution. *Trans. Amer. Philos. Soc.*, 21: 149-191.

Brooks, D. A. 1985. Vernal circulation in the Gulf of Maine. *J. Geophys. Res.* 90: 4687-4705.

Brooks, D. A. and D. W. Townsend. 1989. Variability of the coastal current and nutrient pathways in the eastern Gulf of Maine. *J. Mar. Res.* 47: 303-321.

Christensen, J. P. 1989. Sulfate reduction and carbon oxidation in continental shelf sediments, an examination of offshelf carbon transport. *Cont. Shelf Res.* 9: 223-246.

Christensen, J. P., D. W. Townsend, and J. P. Montoya. 1995. Water column nutrients and sedimentary denitrification in the Gulf of Maine. *Cont. Shelf Res.* 16: 489-515.

Cohen, E. B. and M. D. Grosslein. 1987. Production on Georges Bank compared with other shelf ecosystems. In *Georges Bank*, ed. R.H. Backus, 383-391.Cambridge: MIT Press.

Denman, K. L. and A. W. Herman. 1978. Space-time structure of a continental shelf ecosystem measured by a towed porpoising vehicle. *J. Mar. Res.* 36: 693-714.

Dugdale, R. C. and J. J. Goering. 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. *Limnol. Oceanogr.* 12: 196-206.

Eppley, R. W. and B. J. Peterson. 1979. Particulate organic matter flux and planktonic new production in the deep ocean. *Nature* 282: 677-680.

Garret, C. J. R., J. R. Keeley and D. A. Greenberg. 1978. Tidal mixing versus thermal stratification in the Bay of Fundy and Gulf of Maine. *Atmos. Ocean.* 16: 403-423.

Gieskes, W. W. C. and G. W. Kraay. 1975. The phytoplankton spring bloom in Dutch coastal waters of the North Sea. *Netherlands J. Sea Res.* 9: 166-196.

Graziano, L. M., W. M. Balch, D. Drapeau and B. Bowler. 1996. Seasonal calcification rates and calcite-dependent optical backscattering in the Gulf of Maine. Poster presented at the Gulf of Maine Ecosystem Dynamics: A Scientific Symposium and Workshop, St. Andrews, NB, September 1996.

Jickells, T. 1995. Atmospheric inputs of metals and nutrients to the oceans: their magnitude and effects. *Mar. Chem.* 48: 199-214.

Kaplin, W. A. 1983. Nitrification. Pp. 139-190, In *Nitrogen in the Marine Environment*, eds. E. J. Carpenter and D. G. Capone, Academic Press. 900 pp.

Kempe, S. 1995. Coastal seas: a net source or sink of atmospheric carbon dioxide? LOICZ/R&S/95-1, vi + 27 pp. LOICZ, Texel, The Netherlands.

Lovett, G. M. 1994. Atmospheric deposition of nutrients and pollutants in North America: An ecological perspective. *Ecol. Appl.* 4: 629-650.

Mayer, L. M. et al. 1996. The Kennebec, Sheepscot and Damariscotta River Estuaries: Seasonal Oceanographic Data. *Univ. Maine, Dept. Oceanography Tech. Rept. No. 9601.* 110 pp.

McAdie, H. G. 1994. Atmospheric deposition to the Gulf of Maine. Interim Report to the International Joint Commission, Ottawa, Ontario. 47 pp.

Mosher, B. W., R. W. Talbot and C. E. Jordan. 1996. Atmospheric nitrogen deposition to the Gulf of Maine. Poster presented at the Gulf of Maine Ecosystem Dynamics: A Scientific Symposium and Workshop, St. Andrews, NB, September 1996.

O'Reilly, J. E. and D. A. Busch. 1984. Phytoplankton primary production on the northwestern Atlantic shelf. *Rapp. P-V Reun. Cons. Int. Exp. Mer.* 183, 255-268.

O'Reilly, J. E., C. Evans-Zetlin and D. A. Busch. 1987. Primary production. In *Georges Bank*, ed. R.H. Backus, 220-233. Cambridge: MIT Press.

Paerl, H. W. 1995. Coastal eutrophication in relation to atmospheric nitrogen deposition: Current perspectives. *Ophelia* 41: 237-259.

Pettigrew, N. R., R. D. Hetland and J. P. Wallinga. 1996a. Cyclonic circulation of the eastern Gulf of Maine. Poster presented at the Gulf of Maine Ecosystem Dynamics: A Scientific Symposium and Workshop, St. Andrews, NB, September 1996.

Pettigrew, N. R., D. W. Townsend, R. A. Hyde and C. S. Yentsch. 1996b. The influence of internal waves on the light exposure of phytoplankton. *J. Plankton Res.* (In review).

Pilskaln, C. H., W. Arnold and C. Lehmann. 1996. Particulate flux dynamics in Jordan and Wilkinson Basins: Seasonal POC export and particle resuspension. Poster presented at the Gulf of Maine Ecosystem Dynamics: A Scientific Symposium and Workshop, St. Andrews, NB, September 1996.

Pingree, R. D., P. M. Holligan, G. T. Mardell and R. N. Head. 1976. The influence of physical stability on spring, summer and autumn phytoplankton blooms in the Celtic Sea. *J. of the Marine Biological Association of the United Kingdom*, 56: 845-873.

Rakestraw, N. W. 1936. The occurance and significance of nitrite in the sea. *Biol. Bull., Woods Hole*, 71: 133-167.

Ramp, S. R., R. J. Schlitz, and W. R. Wright. 1985. The deep flow through the Northeast Channel, Gulf of Maine. *J. Phys. Oceanogr.* 15: 1790-1808.

Riley, G. A.1957. Phytoplankton of the North Central Sargasso Sea, 19502. *Limnology and Oceanography*, 2: 252-270.

Riley, G. A. 1967. The plankton of estuaries. In *Estuaries*, ed. G.H. Lauff, 316-326. Washington, D.C.: American Association for the Advancement of Science Publ. 83.

Schlitz, R. J. and E. B. Cohen. 1984. A nitrogen budget for the Gulf of Maine and Georges Bank. *Biol. Oceanogr.* 3: 203-222.

Sharp, J. H. 1983. The distributions of inorganic nitrogen and dissolved and particulate organic nitrogen in the sea. In *Nitrogen in the Marine Environment*, eds. E. J. Carpenter and D. G. Capone, 1-35. Academic Press. 900 pp.

Sherman, K., W. G. Smith, J. R. Green, E. B. Cohen, M. S. Berman, K. A. Marti, and J. R. Goulet. 1987. Zooplankton production and the fisheries of the Northeastern Shelf. In *Georges Bank*, ed. G. Backus, 268-282. Cambridge: MIT Press.

Smith, P. C. 1983. The mean and seasonal circulation off southwest Nova Scotia. *J. Phys. Oceanogr.* 13: 1034-1054.

Sverdrup, H. U. 1953. On conditions for the vernal blooming of phytoplankton. *Journal du Conseil* 18: 287-295.

Townsend, D. W., N. R. Pettigrew, P. J. Brickley, J. Wallinga, F. Chai, A. Thomas, C. S. Yentsch, M. E. Sieracki, C. Garside, D. Phinney and J. Brown. 1996. Internal wave processes in the Gulf of Maine. Poster presented at the Gulf of Maine Ecosystem Dynamics: A Scientific Symposium and Workshop, St. Andrews, NB, September 1996.

Townsend, D. W. 1991. Influences of oceanographic processes on the biological productivity of the Gulf of Maine. *Reviews in Aquat. Sci.* 5: 211-230.

Townsend, D. W. and R. W. Spinrad. 1986. Early spring phytoplankton blooms in the Gulf of Maine. *Cont. Shelf Res.* 6: 515-529.

Townsend, D. W. and J. P. Christensen. 1986. Summertime oceanographic conditions in the Gulf of Maine, 16-24 July 1985: Physical oceanographic, nutrient and chlorophyll data. *Bigelow Lab. Oc. Sci., Tech. Rep. No. 61*. 422p.

Townsend, D. W., L. M. Cammen and M. Morison. 1987. Wintertime oceanographic conditions in the Gulf of Maine, 16-20 February 1987: Chlorophyll, nutrient and hydrographic data. *Bigelow Lab. Oc. Sci., Tech. Rep. No. 62.*

Townsend, D. W., J. P. Christensen, D. K. Stevenson, J. J. Graham and S. B. Chenoweth. 1987. The importance of a plume of tidally-mixed water to the biological oceanography of the Gulf of Maine. *J. Mar. Res.* 45: 699-728.

Townsend, D. W., M. D. Keller, M. E. Sieracki and S. G. Ackleson. 1992. Spring phytoplankton blooms in the absence of vertical water column stability. *Nature* 360: 59-62.

Townsend, D. W., and L. M. Camen. 1988. Potential importance of the timing of spring plankton blooms to benthic-pelagic coupling and recruitment of juvenile demersal fishes. *Biol. Oceanogr.* 5:215-229.

Townsend, D. W., L. M. Cammen, P. M. Holligan, D. E. Campbell and N. R. Pettigrew. 1994. Implications of variability in the timing of spring phytoplankton blooms. *Deep-Sea Res.* 41: 747-765.

Townsend, D. W. and N. R. Pettigrew. 1997. Nitrogen limitation of secondary production on Georges Bank. *J. Plankton Res.* 19:221-235.

Sources, Transport, and Fate of Chemicals of Environmental Concern in the Gulf of Maine: Trace Metals and Organic Compounds

John W. Farrington
Woods Hole Oceanographic Institution

The sources, transport and fate of chemicals govern the distribution of trace metals and organic compounds in coastal, estuarine, and continental margin waters such as those of the Gulf of Maine. From the perspective of concerns for effects on marine organisms, the biogeochemical processes govern the temporal and spatial extent and severity of the field of exposure for organisms. For human health concerns, biogeochemical processes research provides answers about the route back to humans from the aquatic environment and the intensity of exposures for specific chemicals. This paper is a companion paper to the paper by Judith E. McDowell in this volume "Biological Effects of Toxic Chemical Contaminants in the Gulf of Maine".

The Conference Chair asked me to address the following questions:

1. What is the current understanding of the biogeochemical cycling of contaminants of environmental concern in the Gulf of Maine?
2. What are the primary sources of inputs of contaminants? What is the relative importance of point and non-point sources.
3. What are the temporal and spatial variability in distributions and fluxes of these contaminants?
4. What dominant processes control this variability?
5. How important is the coupling between the nearshore and offshore environments?
6. To what extent do we know and understand the processes governing the flux of contaminants from watersheds into the estuaries, nearshore and offshore regions of the Gulf of Maine?

For each of these questions, I will provide a brief overview answer and, for some of these, incorporate a few of the many interesting recent findings. It was suggested by the Conference Chair that this overview paper concentrate on post-1990 findings since 1990 was the year of the most recent Gulf of Maine Conference. Interestingly, at the last conference, there was no explicit review of chemicals of environmental concern. Farrington and Boehm (1989) reviewed organic contaminant data for Georges Bank and some portions of the Gulf of Maine. Larsen (1992) reviewed data for trace metals, chlorinated pesticides, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons in the Gulf of Maine ecosystems. There have been several assessments that included the Gulf of Maine in larger chemical monitoring efforts such as the NOAA Status and Trends Program as discussed in the overview by McDowell (this volume).

Current understanding of the biogeochemical cycling of contaminants of environmental concern in the Gulf of Maine

Our general knowledge of biogeochemical cycling in estuarine, coastal, and continental shelf waters is much improved compared to the status of knowledge in 1990. There have been significant advances in understanding key components of biogeochemical cycles, including the adoption of key fundamental physical chemical concepts for aquatic chemistry (e.g., see Schwarzenbach et al., 1993). Numerical models are poised to provide various scenarios that will guide both research and management efforts (e.g., Adams et al., 1989; Shea, 1995; Connolly, 1991 among many others). Monitoring capabilities are available and ongoing in limited geographic regions providing data that is useful for testing and calibrating test numerical models as well as providing useful information for management purposes. For example, there is a substantive effort associated with monitoring selected trace metals and organic chemicals in Boston Harbor and Massachusetts Bay ecosystems; investigators are examining changes in the waste treatment processes, waste management (e.g., reduction of point sources), and relocation of the Massachusetts Water Resources Authority sewage treatment outfall from the harbor to the bay.

The biogeochemical models are being integrated with physical dynamic models of water mixing, water flow, and resuspension and sediment transport as well as with pharmacological/toxicological models for organisms. Attempts to develop easy to use desktop computer multimedia models for predicting chemical risks from environmental exposures are evolving but need further refinement and validations (Renner, 1995).

Given the intensity of concern with environmental quality considerations associated with nearshore coastal regions, and especially urban harbor areas polluted by decades of deliberate and inadvertent waste disposal, it is not a surprise that we know more about the near shore-estuarine and harbor regions than we do about the offshore regions. The well known "bath-tub ring effect" of higher contaminant concentrations in the near shore, especially the urban harbor areas, has been revalidated in several studies.

Primary sources of inputs of contaminants and the relative importance of point and non-point sources

This varies from region to region and chemical by chemical. However, I propose some general statements:
1. It appears that there has been success with managing and achieving point-source reductions in some locations. The current and future reductions of point-source inputs leaves other sources as predominant. If further reductions of inputs of selected chemicals of environmental concern are warranted or desired, then non-point sources should be targeted. The non-point sources of continuing importance are atmospheric inputs, urban and agricultural land run-off, and inputs to the benthos and overlying water column from previously contaminated sediments.
2. The challenge of assessing the relative contributions of major riverine inputs to the Gulf of Maine and comparison of these with atmospheric inputs is yielding slowly to field program measurements for riverine systems; but there are few atmospheric measurements over the Gulf.
3. Return flux from contaminated sediments in several harbors, and by inference, from potential sources of newly discharged harbor dredge spoils, continues to appear to be a source of concern for selected chemicals of environmental concern (e.g., NRC, 1989,1997).

Temporal and spatial variability in distributions and fluxes of these contaminants

To address this issue on a Gulf-wide basis requires a synthesis of data that is fraught with difficulties of comparability of data collected by various investigators at different points in time with attendant quality control and quality assurance problems. Nevertheless, a data base for measurements of chemical contaminants in sediments is being assembled and is almost complete (Buchholtz ten Brink et al., 1995). This data base verifies something that is no surprise to Gulf of Maine researchers, there are many more sampling stations and data points for analyses of chemicals of environmental concern in sediments in the nearshore regions than in the offshore basins. Using this data base, Bothner et al. reported (this volume) that between 1977 and 1993 there was an average of a 46% decrease in Pb concentrations in the upper 2 cm of sediments at four locations in outer Boston Harbor.

As McDowell reports in this volume, monitoring programs using bivalves as sentinel organisms have continued in the Gulf of Maine as part of the U.S. NOAA National Status and Trends Program and a regional program, Gulfwatch, involving Canadian and U.S. stations in the Gulf of Maine has been undertaken. A recent report (Jones et al., 1997) for Gulfwatch efforts 1991-1995 reports data for chemical measurements of selected trace metals and organic chemicals in mussels which generally shows a southward trend of increasing concentrations of selected heavy metals, chlorinated pesticides, polycyclic aromatic hydrocarbons and PCB congeners consistent with the fact that there are more urban areas in the southern Gulf of Maine coastal area compared to the northern regions. During the period of 1991-1995, Gulfwatch data do not show significant temporal trends for trace metals or organic chemicals of environmental concern.

Dominant processes that control this variability

The most important processes controlling temporal and spatial variability are as follows.

1. Human intervention either in effectively reducing inputs due to management of use of chemicals or in moving point sources of input, e.g., the relocation of sewage outfalls or movement of contaminated harbor sediments by dredging.
2. Seasonal biological activity associated with primary production of phytoplankton in the Gulf of Maine waters and resulting particulate matter flux with associated chemical contaminants through the water column as shown from the combined results of the posters/presentations at this symposium by Pilskan et al., Pike et al., Charette and Moran, among others, for the Wilkinson and Jordan Basins.
3. Physical dynamics of the nearshore and offshore waters governed by tidal and wind-driven circulation and mixing.

The result of substantive efforts over the years of Wallace and co-workers (e.g., Krahforst and Wallace and Wallace this symposium) Bothner and co-workers, and recent results of Moran and co-workers - much of this reported or reviewed in papers at this symposium - provide valuable understanding of the biogeochemical cycles of trace metals in the Gulf of Maine and, by inference, biogeochemical cycles of organic contaminants.

Understanding the physical-chemical composition and form of the particulate matter, whether in the water column or in the sediments - especially the organic matrix - has emerged as an important factor for water-particle partitioning and, by inference, biological availability.

One example of recent progress is our increased understanding of the details of the biogeochemistry of polycyclic aromatic hydrocarbons in the Gulf of Maine urban harbor sediments. McGroddy and Farrington (1995) reported that polycyclic aromatic hydrocarbons in Boston Harbor sediments were partitioned between solid phases and pore water phases in a manner suggesting that a large portion of PAH were not readily available for equilibrium partitioning. Desorption experiments in the laboratory confirmed these results (McGroddy et al., 1996). We hypothesized that association with soot might be the explanation for the PAHs not being readily available for partitioning. Soon thereafter, Gustaffson et al. (1997) reported on measurements of soot in several of the samples from two of our cores and other sediment cores and, using partition coefficients for PAH sorbed to black carbon, showed that partitioning of the PAH to soot particles quantitatively explained the pore water-solid phase partitioning results. All of these result have important implications for bioavailability and for setting Sediment Quality Criteria as discussed in the cited papers.

The importance of coupling between the nearshore and offshore environments

Compelling evidence of the importance of this coupling comes from the studies to be reported at this symposium by Signell and co-workers for biological and physical modeling of red tide organisms in the Western Gulf of Maine. On a first order basis, much of what is learned from this effort applies to the chemical contaminants which are transported as both dissolved and particulate phases.

Processes governing the flux of contaminants from watersheds into the estuaries, nearshore and offshore regions of the Gulf of Maine

Several recent efforts have provided, or are now providing, an understanding of the role of land use patterns and other human activities in influencing chemical contaminant loadings for rivers as they flow to the sea. Papers at this symposium by Studer at al. and Romanov et al. contribute to this growing knowledge base for trace metals and organics. The tricky part, as it has been for many decades, is to understand what happens in the transition zone between fresh and saline waters — the through-the-estuary flux and speciation challenge. Mayer et al., in their work reported at this symposium, provide a powerful example of variability between estuaries for processes controlling types and amounts of particulate matter with comparisons of three Maine estuaries.

Conclusions and Recommendations

Current knowledge of the biogeochemical cycles of several chemical contaminants and the status and trends of their presence in several compartments of the Gulf of Maine Ecosystems clearly defines that society "dodged several chemical bullets" when much less data, applying first principles, and intuitive reasoning led to reductions of chemical contaminant inputs beginning in the late 1960s and early 1970s. There have been significant advances in our understanding of the inputs, transport, fate and bioavailability of trace metals and organic chemicals of environmental concern since 1990. These advances have come from a combination of both research and monitoring programs. While most of these advances have been concentrated in nearshore waters, there have been some significant advances related to offshore- Gulf of Maine Basins areas.

Five recommendations, among many I could make, seem most important to me at this time.

1. There are continuing needs to better quantify the inputs to the Gulf of Maine of chemicals of environmental concern from rivers, groundwater, land runoff, and the atmosphere.
2. The bioavailability of chemicals of environmental concern in contaminated urban harbor sediments (and dredged harbor sediments) and the release of these chemicals to the overlying waters continues to be an important research topic of societal importance.
3. New advances in knowledge and sampling and measurement technologies make it feasible to make significant progress in understanding the biogeochemistry of chemicals in the basins and other offshore waters of the Gulf of Maine. Now is the time to move forward in this effort.
4. There is an important need to increase the effort to provide coupled numerical models of biogeochemical cycles, bioavailability, and biological effects; and to test such models against realistic field data sets.
5. A large scale 'biogeochemical experiment' is in progress with the move of the MWRA outfall from Boston Harbor to Massachusetts Bay. The importance from a policy and management perspective in protecting valuable living natural resources and public health is obvious. In addition, there is an opportunity to learn much from what happens to the chemicals released by the outfall as they are discharged to Massachusetts Bay. Furthermore, this shift in outfalls will change the chemistry of Boston Harbor. Again an 'experiment' crying out for study. While reputable scientists would not propose such experiments with nature for the sake of experimentation alone, it is incumbent for the scientific community to learn from these 'societal experiments' to provide knowledge of generic value worldwide.

A productive mix of funding from various agencies and programs for both research and for monitoring has supported numerous scientists and engineers in the efforts yielding the advances in our knowledge. This needs explicit recognition because there are troubling indications that some of these sources of funds are in jeopardy. I am less familiar with the sources of funding in Canada except to state that they are important and vital to the continuing research and monitoring effort. A non-exhaustive list of U.S.- based efforts, not in order of importance, includes state government agency funding for agency scientists efforts, Gulf of Maine Regional Marine Research Program, MWRA internal and external funding, U. S. Army Corps of Engineers, U. S. Environmental Protection Agency, U. S. Geological Survey funding of U.S.G.S. and external scientists, U.S. NOAA Sea Grant, U.S. NOAA Status and Trends Program, U.S. National Science Foundation, U.S. Office of Naval Research.

I strongly support the efforts underway to bring closer connectivity between research, monitoring, policy and management (e.g., NRC, 1995). Also, I strongly advocate continuing support of research which provides knowledge of the biogeochemistry and biological effects of chemicals of environmental concern in the Gulf of Maine. In the popular rush to better integrate scientific research and new knowledge into the policy-management arenas, society cannot afford to deplete the 'working capital' of new knowledge upon which the investment yields of wise policy and management are firmly founded.

References

Adams, E. E., R. F. Kossik, D. J. Cosler, J. K. MacFarland, P. M. Gschwend. 1989. Calibration of a transport model using halocarbons from sewage as tracers. In *Estuarine and Coastal Modeling*. ed. M. Spaulding, 472-481.

Buchholtz ten Brink, M., F. T. Manheim, J. C. Hathaway, S. H. Jones, L. Ward, P. F. Larsen, B. W. Tripp, J. W. Farrington, G. T. Wallace Jr. 1995. Gulf of Maine contaminated sediment data base; compilation, desk-top access, and analysis of existing data for scientific and policy needs. Progress Report for NOAA Project Number GMR-06. U. S. G. S. , Woods Hole, MA. 29 pp.

Connolly, J. P. 1991. Application of a food chain model to polychlorinated biphenyl contamination of the lobster and winter flounder food chains in New Bedford Harbor. Environ. Sci and Technol. 25: 760-770.

Farrington, J. W. and P. D. Boehm. 1987. Natural and pollutant organic compounds. In Georges Bank. eds. R. H. Backus and D. W. Bourne, 197-207. Cambridge: The MIT Press.

Gustaffson, O., F. Haghseta, C. Chan, J. Macfarlane, P.M. Gschwend. 1997. Quantification of the dilute sedimentary 'soot phase': implications for PAH speciation and bioavailability. Environ. Sci. Technol. 31:203-209.

Jones, S. H., M. Chase, J. Sowles, W. Robinson, P. Hennigar, G. Harding, D. Taylor, P. Wells, J. Pederson, K. Coombs, K. Freeman, L. Mucklow. The first five years of Gulfwatch, 1991-1995: a review of the program and results. Jackson Estuarine Laboratory, University of New Hamphire, Durham, New Hampshire. 166pp.

Larsen, P. F. 1992. An overview of the environmental quality of the Gulf of Maine. In. The Gulf of Maine, eds. D. W. Townsend and P. F. Larsen, 71-95. NOAA Coastal Ocean Program Regional Synthesis Series Number 1. U. S. Department of Commerce. NOAA Coastal Ocean Program Office, Washington, D. C.

McGroddy, S. E. and J. W. Farrington. 1995. Sediment pore-water partitioning of polycyclic aromatic hydrocarbons in three cores from Boston Harbor, Massachusetts. Environ. Sci. Technol. 29:1542-1550.

McGroddy, S. E., J. W. Farrington, and P. M. Gschwend. 1996. Comparison of the *in situ* and desorption sediment-water partitioning of polycyclic aromatic hydrocarbons and polychlorinated biphenyls. Environ. Sci. Technol. 30: 172-177.

NRC. 1989. Contaminated marine sediments - assessment and remediation. National Research Council, National Academy Press, Washington, D. C. 493pp.

NRC. 1995. Improving interactions between coastal science and policy. Proceedings of the Gulf of Maine Symposium. National Research Council, National Academy Press, Washington, D.C. 259 pp.

NRC. 1997. Contaminated sediments in ports and waterways. National Research Council, Washington, D.C. 295pp.

Renner, R. 1995. Predicting chemical risk with multimedia fate models. Environ. Sci. Technol. 29: 556A-559A.

Schwarzenbach, R. P., P. M. Gschwend, D. M. Imboden. 1993. Environmental Organic Chemistry. John Wiley and Sons, Inc. New York. 681 pp.

Shea, D. 1995. Multimedia Fate Model of Organic Contaminants in Massachusetts Bay. Environmental Quality Department Technical Report Series No. 95-18. Massachusetts Water Resources Authority, Boston, MA. 15pp.

Physical Disturbance Agents and Habitat Disruption in the Gulf of Maine

Les Watling
University of Maine

"New opinions are always suspected, and usually opposed, without any other reason but because they are not already common."
John Locke (1632—1704)
English philosopher. Dedicatory Epistle to *An Enquiry Concerning Human Understanding* (1690).

"A point of view can be a dangerous luxury when substituted for insight and understanding."
Marshall McLuhan (1911—80)
Canadian communications theorist. *The Gutenberg Galaxy,* "Typographic Man Can Express but Is Helpless to Read the Configuration of Print Technology" (1962).

Abstract

The sea bottom is subject to a variety of natural and anthropogenic forces that result in physical disturbance of the habitat. Natural physical disturbances include waves, currents, iceberg scour, and the activities of marine animals including foraging and bioturbation. Most of the Gulf of Maine is greater than 70 m in depth. Consequently, the more intense forces such as wave and current motion have little impact on most of the sea bottom. In addition, anthropogenic activities, such as channel dredging, gravel mining, and wetland filling, are either not widely practiced or are subject to strong regulation. On the other hand, the use of mobile fishing gear in all areas of the Gulf of Maine has introduced a physical disturbance agent into areas that otherwise would never see such disruptive forces. From the available evidence, it appears that the use of such gear has resulted in the loss of structural complexity over most of the sea bottom, and there most likely has been, or will be, a concomitant loss of biodiversity. The longer term ramifications of this alteration of the ecosystem are unknown.

Introduction

Much has been written concerning the potential impacts of chemical pollutants in the sediments on the fauna of the Gulf of Maine, yet there has been scant evidence that these compounds have caused *widespread* problems (see the "so what" section of White and Robertson 1996), although specific sites near large urban centers have been shown to have high contaminant levels (e.g., see the review of Buchholtz ten Brink et al. 1996; Kennicutt et al. 1994) and one species has been seen to have developed tumors (Yevich and Barszcz 1977). As yet un-investigated in Gulf of Maine waters are the effects of "endocrine blockers," compounds that cause hormonal problems in marine mammals (Rolland and Colborn 1996). In general, however, most chemical pollutants will impact species over a time scale of multiple generations, yet a great deal of attention has been paid to understanding their inputs, distributions, and ultimate environmental fates. On the other hand, little has been said about other types of stressors on marine organisms, in particular, those such as physical disturbance agents which disrupt habitat and impact species on the time scale of a single generation. While there are both natural and anthropogenic physical disturbances, the focus of this paper will be on those related to human uses of the natural resources of the Gulf of Maine, filling of wetlands, dredging of harbors and channels, and in particular, the use of mobile fishing gear.

The central argument of this paper can be outlined as follows:
There are many physical disturbance agents that affect marine benthic habitats, whether inshore along the coast

or offshore in the deep basins. Of them all, however, mobile fishing gear as generally deployed, disturbs the upper several centimeters of the ocean bottom, covers the greatest area, and is used with the greatest frequency. Consequently, of all the disturbance agents, mobile fishing gear has the highest intensity (force per unit area) and severity (loss of biomass of resident species).

From a review of the scientific literature, it is possible, for the benthic communities known to exist in the Gulf of Maine, to identify which would be most likely heavily impacted and which would be best able to withstand the effects of trawling. Further study, as advocated under current management rules such as Amendment #7 to the Northeast Multispecies Fishery Management Plan[1], would enhance our knowledge of rates of processes, such as the rate of recovery of the impacted areas, etc., but would add nothing to our ability to predict which specific areas would be severely altered by the use of mobile fishing gear.

Disturbance Agents and Their Likely Effects in the Gulf of Maine

Most of the sea bottom consists of unconsolidated sediments which can be subject to a variety of physical disturbances, that is, the disruption or movement of the sediment. Agents of physical disturbance include abiotic hydrodynamic processes such as tidal currents or wave generated currents, bioturbation processes, which might include animal burrowing and tunneling, and anthropogenic processes of which fishing, dredging, and gravel extraction are the best examples. Each of these agents differ in terms of the *intensity* and *severity* of the disturbance they produce (Hall 1994), with the result that the ability and/or time required for the benthic community to recover will also differ considerably. Intensity here is measured as the physical force of an event per unit of time (White & Pickett 1985); for example, the bed shear stress caused by waves that might result in sediment movement or resuspension, or the ploughing effect of an iceberg (at the large end of the scale) or bivalve mollusk (at the small end of the scale). Severity is a measure of the impact of the disturbance on the organisms, benthic community, or ecosystem; that is, the proportion of individuals removed or killed, the energetic cost of rebuilding burrows or tubes, etc. (Hall 1994). For each of the major disturbance agents likely to be operating in the Gulf of Maine, a summary estimate of their intensity and severity will be given.

Abiotic

Waves: Very large storm waves can impact the bottom at maximum depths of about 30-40 m, with attendant current velocity increases seen at 60-70 m (see review in Hall 1994). As with tidal currents, storm waves will act to remove fine sediment from rough bottom habitats, thus maintaining communities with large abundances of emergent epifauna. For most of the Gulf of Maine wave impacts will be important only in the narrow zone just offshore of the exposed headlands of the outer coast. For example, Witman (1987) noted that horse mussels were excluded from depths <9m at many wave exposed sites and that storm-related dislodgment represents the most significant source of mortality for the species. On Georges Bank, which is a relatively shallow offshore habitat, most of the area will be affected by storm waves, and areas such as the Great South Channel will be maintained as cobble and boulder bottom. *Intensity* - high during major storm events; *Severity* - low, since most species living in storm affected areas are adapted to these types of events.

Currents: Nearshore tidal currents can exceed the critical erosion velocity for all but the largest sediment particles resulting in bottoms of cobble and sand. Offshore in deeper waters currents rarely exceed critical erosion velocity for silt-sized particles, that is, about 25 cm s^{-1} (see review of factors in Nowell et al. 1981). While current meter data to substantiate this claim may be lacking for large areas of the Gulf of Maine, indirect evidence exists in the form of visual inspection of sediments and rock surfaces which are usually seen to be draped with a fine layer of silt. *Intensity* - low since bed shear stresses over most of the Gulf of Maine are lower than critical velocities for sediment movement; *Severity*- low since animal biomass in these areas is rarely lost due to current movements.

Iceberg scour: While of potential importance on the Grand Banks of Newfoundland, icebergs have not been an important agent of disturbance in the Gulf of Maine for about 12,500 years (Schnitker 1986). *Intensity* -

[1] Amendment #7 to the Northeast Multispecies Fisheries Management Plan, incorporating the Supplemental Environmental Impact Statement, Volume 1. New England Fishery Management Council (1996).

high since digging of iceberg into sediment results in mass sediment movement; *Severity* - high due to large numbers of animals killed during sediment movement.

Biotic

Bioturbation: As animals move through marine sediments they tend to shift the sediment particles, thereby also disrupting the lives of smaller sediment inhabitants. Most of sediment movement is very local, with the result that the sediment particles are recycled in the immediate vicinity of the bioturbating organism (Wheatcroft et al. 1990). Therefore, while sediment movement rates may be high (on the order of thousands of litres of sediment shifted per m^2 per year), sediment particles (and the binding organic matrix) are generally not lost to the surrounding environment and the animals living in those sediments are most likely unable to detect the movements of the individual mineral grains. *Intensity* - low since sediment grains are usually moved a few at a time resulting in almost unmeasurable bed shear stresses; *Severity* - low because all sediment dwellers have time to alter or repair their burrows or tubes as other animals are shifting sediment particles.

Foraging predators: In some areas of the world, very large predators, such as gray whales, may remove up to 6 m^2 of the sediment surface in one bite (Oliver & Slattery 1985), while fish and birds may create empty patches on the order of 10's of cm^2 (Hall et al. 1994). This type of foraging can be successful only in areas where there are large aggregations of highly nutritious prey species (members of the genus *Ampelisca* in the case of the gray whales) living in soft sediments. It is likely that predator foraging of the American Plaice (which takes mouthfuls of sediment in order to prey on brittle stars) may be important in Wilkinson Basin, but otherwise this disturbance agent is probably not of great significance for most of the Gulf of Maine, since bottom feeding whales, walruses, and rays are uncommon. *Intensity* - high locally but low on an aerial basis since the activity affects only a tiny fraction of the bottom; *Severity* - high locally but low for the Gulf of Maine as a whole.

Human activities

Harbor Channel Dredging and Spoil Disposal: Dredging of the sea bottom in the vicinity of the harbors and channels along the coast of the Gulf of Maine is a relatively common occurrence. This type of activity results in the complete removal of the upper sediment layers and resident biota from the area being dredged, and the deposition of sediment onto an area of sea bottom that may differ substantially in both sediment characteristics as well as biota. There will, therefore, most likely be a change in the fauna at the receiving site. Because of the large number of marine invertebrate species that reproduce by means of pelagic larvae, and the tendency of many "infaunal" species to leave the bottom at night, recolonization of both the dredged and disposal sites is usually rapid. These new colonizers are not likely to be of the same species as the original inhabitants, however, and it may take several years for the dredged site to return to a community composition approximating the pre-dredge conditions (Rhoads et al. 1978). It should be noted also that since the sediments being removed are often heavily polluted (especially those from harbors) this issue is as much one of contaminant dispersal as it is one of physical disturbance. Because dredging is restricted in areal extent, it is probably not an important disturbance agent when the entire area of the Gulf of Maine is considered. *Intensity* - high locally but low for the Gulf of Maine as a whole; *Severity* - high locally but low for the Gulf of Maine as a whole.

Sand and Gravel Extraction: Contrary to expectations, gravel beds have very high biodiversity, primarily because the individual sediment particles are quite large and pack loosely, leaving interstitial spaces large enough to be inhabited by the resident infaunal species. Since these gravel beds are also near shore, they receive a steady input of plant fragments which settle into the interstitial spaces as well. The plant debris provides substratum for bacteria, which are then a food source for the invertebrates (personal observations for a gravel bed off Seguin Island, Maine). Consequently, gravel beds can harbor large numbers of individuals as well as a high diversity of species. When gravel is mined, the entire resident fauna is removed. The degree to which the gravel infauna is impacted will be a function of the area of gravel being removed as well as the recolonization rate of the resident species. The potential for permanent habitat alteration and significant loss of biodiversity is quite high, and is just now being studied in the seas around the British Isles. Gravel beds in the Gulf of Maine have not yet been exploited, but the impact of gravel extraction is likely to be significant if such activities occur here. *Intensity* - high in area of activity; *Severity* - very high where such activities occur.

Filling of Wetlands: According to updated figures listed in Thomas (1996), the U.S. part of the Gulf of Maine possessed 813,078 hectares of coastal wetlands, including fresh, brackish, and marine habitats. Of these, only 13% (109,069 ha) comprised tidal flats and a further 5% (41,215 ha) salt marsh. Almost all of the remainder was coastal forested and scrub shrub wetlands. In addition, data presented by Thomas (1996) indicates that at least from the mid 1980s none of the states bordering the Gulf of Maine experienced net losses of wetlands, and only Massachusetts had small wetland losses from the mid 1970s to mid 1980s. When wetland losses do occur, generally the area lost is small and localized, but the loss of habitat is complete and there is no chance of recovery at that specific site (although there may be some possibility of wetland addition through remediation). Wetland losses are, therefore, significant when they occur, but under current management laws, are not likely to impact very large areas, even taken cumulatively. *Intensity* - high; *Severity* - very high.

Fishing: The process of removing fish from the sea bottom can be accomplished through a variety of means. The most widespread activities, which disturb significant areas of the seafloor, are trawling and dredging. These types of mobile gear cover large areas, both individually and in aggregate, and exert heavy downward forces on the sediment-water interface. We recognize that longlines, gillnets, and traps produce impacts as well. However, their use is more restricted and impacts are extremely localized. The exact nature of the disturbance, and its consequences for the resident fauna, however, is dependent upon the composition of the bottom sediments. Research conducted so far in this area has been reviewed by Messieh et al. (1991), Hall (1994), Hall et al. (1994), and Dayton et al. (1995). The major studies are summarized below. For the Gulf of Maine the areal extent and severity of physical disturbance due to trawling and dredging far outstrips all of the other agents noted above. It is the only agent of disturbance that occurs nearly everywhere (including at present cobble and boulder bottoms due to the development of rock-hopper gear), and in many areas occurs several times per year, thus curtailing the ability of annual reproducers to recolonize the disturbed habitats. *Intensity* - moderate to high depending on the substratum composition, that is, resuspension of bottom sediments will be highest in fine sediment basins, and lowest on sandy bottoms; *Severity* - moderate to high, again depending on the habitat, i.e., sand bottom communities will see little loss of biomass, although the smoothing of the sand waves and spreading of shell aggregates will change the habitat; on mud bottoms tube dwellers will have their tubes destroyed and large epifaunal organisms will be removed from the gravel and boulder bottoms.

Summary of Impacts of Disturbance Agents

There are several agents of physical disturbance that might alter the structural complexity of a benthic community. Most of the natural agents outlined above operate over small physiographic regions and have been a force structuring benthic communities for millions of years. Anthropogenic activities such as channel dredging, gravel extraction, and wetland filling, while severe, occur infrequently and are limited in extent. Fishing activities (using mobile fishing gear) "mimic" the natural physical disturbance agents on some bottom types, for example in sandy areas, which are inhabited by species adapted to being excavated or resuspended and therefore have the capability to rebury themselves. On the other hand, fishing activities differ from all other physical agents of disturbance in several important aspects: 1) the area of coverage of the disturbance is extremely large, often leaving few or no undisturbed patches within the fishing area; 2) trawling and dredging are agents that can operate in areas of the sea bottom normally isolated from physical disturbance, such as below the storm wave base or in depositional basins; and 3) the severity of the disturbance is often unusually high, for example, resulting in the removal of large amounts of biomass of epifaunal organisms, or destruction of large tubes which have been constructed over the entire lifetime of individual fine-sediment dwellers and which cannot be re-made when broken.

Effects of Mobile Fishing Gear on Marine Benthic Communities

Linkages Between Habitat Variability And Population Processes

The ecological literature contains many studies which demonstrate the role of habitat structure in regulating population dynamics and species interactions of fish communities. Examples include coral reefs, seagrass beds, rock reefs, and kelp beds (e.g., Heck and Orth 1980, Ebeling and Hixon 1991). Much less work has been done in deeper water outer continental shelf regions. Field studies have shown that juveniles of many fish species and other mobile fauna exhibit associations with many types of small-scale habitat features (e.g., Grimes et al. 1986, Lough et al. 1989, Auster et al., 1994, 1995, Langton et al. 1995, Tupper and Boutilier 1995) such as biogenic depressions, cobble, shell, burrows, macroalgae, sand wave crests, sponges, and amphipod tubes. The use of these features may or may not be essential for the completion of any life history stage of a species, that is, in terms of creating a demographic bottleneck, yet habitat complexity seems to increase survivorship of individuals by providing cover from predators.

Laboratory studies have shown that the use of various habitat features can be important in reducing the efficiency of predators. Juvenile cod *(Gadus morhua)* shifted their substrate preference from less to more complex habitat (i.e., sand or gravel-pebble to cobble) in the presence of a predator, significantly increasing their survivorship (Gotceitas and Brown 1993). Individuals used the interstices of the cobble substrate for refuge, illustrating that even subtle changes in habitat complexity can have an effect on predation pattern. Behavioral responses to increased habitat complexity have also been shown to increase survivorship in early benthic phase American lobster, *Homarus americanus* (Wahle 1992a, 1992b, Wahle and Steneck 1992).

Field studies also support this analysis. Lough et al. (1989) found that the pelagic juvenile stage of Atlantic cod occurred over large areas of Georges Bank, but benthic phase juveniles only occurred on the gravel habitat of the Northeast Peak. Assuming that cod settled everywhere, predation pressure may be responsible for this pattern of differential survival. More recent work by Tupper and Boutilier (1995) off Nova Scotia demonstrated that survivorship and growth of cod increased with habitat complexity. They noted that juvenile Atlantic cod settled in all habitats (i.e., sand, seagrass, cobble, and rock reef) but growth, survivorship, and density were higher in more complex habitats.

Mobile Fishing Gear Impacts on Habitat Structure

Studies of mobile fishing gear impacts, using objective measures of change, such as differences in numbers or biomass, comprise two types: (1) experimental studies where an area of the sea bottom is disturbed by fishing gear in a controlled manner and the fauna compared with an undisturbed ambient area; and (2) observational studies where a fished area is compared with an undisturbed area either off-limits to fishing or before fishing commenced. Results from the two types of studies are summarized in Tables 1 and 2 (next page).

Note that all experimental studies were done in shallow waters on substrates that are generally hard or clean, that is, with very little silt or clay. Since the bottoms are primarily sands, most of these sites either have strong currents or suffer the effects of storm waves. In either case, the benthic infauna would be adapted to frequent physical disturbances. Missing are studies from depths below the storm wave base, as well as experimental studies in areas of significant epifaunal growth. The observational studies, on the other hand, have been conducted in just those areas where experimental studies would be difficult. In the North Sea, Riesen and Reise (1982) and Reise (1982) note that the epifauna, especially the large *Sabellaria* reefs, have already been removed. In areas where there has been substantial fishing pressure on bottoms with large epifaunal, colonial invertebrates, especially sponges and cnidarians, there is clear evidence of the epifauna being removed by the fishing gear (e.g., Bradstock & Gordon 1983, Sainsbury 1991). This same trend has been documented recently for Jeffreys Bank in the Gulf of Maine (Auster et al. 1996, originally published as NAFO SCR Doc. 95/21). In all these cases either the by-catch drops with time, the catch of target species using the structurally complex bottom decreases, or there is visual evidence from submersible or ROV studies.

In general, it can be concluded that mobile fishing gear has at least three major effects when used in areas of the sea bottom where natural physical disturbances do not occur:

1. In "hard bottom" areas, that is, where the sea bottom consists of gravel with large boulders and there is an abundance of emergent epifauna, the structural complexity of the bottom community is reduced. As the larger epifaunal invertebrates, such as sponges, cnidarians, and bryozoans are removed and boulders are moved along the bottom, available habitat for a myriad of small species is lost, thus decreasing the overall biodiversity.
2. Homogenization of the bottom results in loss of criti-

Table 1.
Results of experimental studies of trawling and dredging impacts on benthic communities

Trawl or dredge	Substrate type, depth	Region	Study conditions	Results	Author
beam trawl, 2 m	sand, 20 m	southern North Sea	site hauled once; number of tickler chains altered	Sessile organisms such as hydroids, tube making polychaetes, light-shelled bivalves and echinoids were badly damaged. Mobile macrofauna not affected	DeGroot & Apeldoorn, 1971
beam trawl	coarse sand with shell, 20 m	Southern North Sea	area trawled 6 times; catches compared	No decrease in density of megafauna caught in subsequent trawls; macrofauna not sampled by grab, etc.	Craymeersch 1994
beam trawl, 12 m	sand, well packed, 30 m	southern North Sea	area trawled 3 times; sampling by box core pre- and immediately post-drag	Decreased abundance of small heart urchins, and various polychaetes; increased abundance of small tellinids and magelonids, possibly due to redistribution in sediment	Bergman & Hup, 1992
beam trawl, 4 m	gravel, cobble, 32 m	Irish Sea	10 hauls with 4 m and 3 with 2 m beam trawl; catches compared	Density of sessile epifauna reduced 50%	Kaiser & Spencer 1994
otter trawl, 20 m footrope and 90 kg doors	very fine mud, 20 m	Maine, USA	site hauled once; sampled 1 d post-drag.	Surface sediment lost	Mayer et al., 1991
otter trawl	sand, 10 m	New South Wales, Australia	area trawled repeatedly for one week; samples pre- and post-trawl by grab	Most infauna were rare making comparisons difficult; however, there appeared to be no difference in the faunal composition pre- and post-trawling	Gibbs, et al., 1980
roller-rigged otter trawl	gravel, cobble, 20 m	Georgia, USA	area trawled once; area surveyed by divers	Heavy damage only to barrel sponges; slight damage to octocorals; all recovered after twelve months	Van Dolah, et al., 1987
scallop dredge	muddy sand, 4 m	Maine, USA	site hauled many times; sampled 3 times over 5 mo. pre-drag and 3 times over 9 mo. post-drag	Upper 4 cm of sediment lost; sediment coarsened. Recovery took 9 months for amino acids, total microbial biomass, and total abundances of cumaceans, and phoxocephalid and photid amphipods.	Watling et al., unpublished
scallop dredge	coarse sand, 5 m	New Zealand	5 parallel tows, once on each section of bottom; samples at 0 d & 3 mo. post-drag.	Phoxocephalid and urothoid amphipods, tanaids, and some polychaetes showed reduced abundances at one site, whereas, ostracods, mollusks, and other polychaetes were strongly affected at the second site.	Thrush et. al., 1995
scallop dredge	sand, 5 m	Scotland	several tows over the same track over 9 d; samples at 1-5 & 9 d.	Infauna numbers tended to increase with increasing dredge activity, but biomass decreased. Sessile polychaetes, heart urchins, and sand eels suffered greatest decreases.	Eleftheriou & Robertson, 1992
scallop dredge	poorly sorted mud with shell hash, 8 m	Maine, USA	site hauled once; sampled 1 d post-drag	Surface labile organic matter (especially chlorophyll and protein) lost from upper 2 cm, some due to resuspension and some to burial. Surface layers also became enriched in anaerobic microbiota.	Mayer et al., 1991

Table 2.
Summary of observations on trawled or dredged sites, with inferences being drawn about disturbance mechanism. All sites chosen have high probability of having been disturbed by fishing activities.

Substrate type	Region	Trawl or dredge	Observations	Author
sand & cobble, with extensive bryozoan beds; 10-35 m depth	New Zealand	otter trawl with chains and rollers	No trawling in the grounds until synthetic fibres were available. Extensive trawling from 1960s to 1970 then destroyed almost all the bryozoan beds, considered to be a nursery area for snapper. Trawling prohibited in 1980.	Bradstock and Gordon, 1983
sand with extensive epibenthic organisms; 50-200 m depth	Australia, NW shelf	otter trawls	Area not trawled until 1959. Extensive trawling by Japanese and Taiwanese produced tons of by-catch and resulted in shift of major fish species being caught. Preferred species were associated with epibenthic colonial invertebrates. Half of shelf closed to trawling by 1987; recovery is being monitored.	Sainsbury, 1991; Sainsbury et al., 1993
gravel bank with mud overlay; 100 m depth	Gulf of Maine, Jeffreys Bank	otter trawls	Extensive sponge community observed in 1987; repeat observations in 1993 showed overturned boulders and reduced cover of sponges. Area may be a refuge for juvenile gadoids.	Watling, unpublished; Auster et al., 1996
sand, cobble, and shell; 30-40 m depth	Gulf of Maine, Swans Island	scallop dredge and otter trawl	Reference and fished sites surveyed by ROV video. Epifaunal organisms dominant in reference areas; cover of these species decreased in fished areas.	Auster et al., 1996.
sand, boulders; 80 m depth	Gulf of Maine, Fippennies Ledge	scallop dredge	Area fished for scallops showed reduced densities of scallops, polychaetes (Myxicola) and tube-dwelling anemones (Cerianthus) as observed by submersible photos.	Langton & Robinson, 1990
sand	Gulf of Maine, Stellwagen Bank	scallop dredge	Dredge path and adjacent areas examined with ROV video. Dredge path identified as linear strips devoid of benthic microalgae. Hydroids were dense in undisturbed area but eliminated from dredge path. Shrimp density increased with increased hydroid density outside of dredge path but were absent in dredge path.	Auster et al., 1996.
sand	Gulf of Carpenteria, Australia	prawn trawl	Areas fished for 20 years were surveyed before and after opening for prawn trawl fishery. The numerical abundance of 52 of 82 fish species remained unchanged. 30 taxa changed in abundance, some decreased (benthic) and others (bentho-pelagic) increased. Impacts on invertebrates were not reported.	Harris & Poiner, 1991
sand	SW Australia	prawn and scallop trawls	Areas open and closed to trawling were surveyed for bycatch (primarily fish). Trawled and untrawled areas were not significantly different in their catch. One area, with seagrass and not trawled had very high biodiversity. Impact of trawling is considered to be low because the target species live primarily on open sand bottoms.	Laurenson et al., 1993.

cal habitat features of importance to the survival of recruits. For important fishery species loss of nursery habitat can mean progressive decline in economically important species.

3. In "soft sediment" areas, that is, bottoms where the sediment is dominated by silts and clays, also thought of as muddy bottoms, homogenization of the upper sediment layers results in collapsing of burrows and breaking of tubes in which small invertebrates live. Many of these species are incapable of excavating a new burrow to the sediment surface or constructing a new tube once they've reached a certain life history stage. Consequently, there is again a significant loss of biodiversity.

It must be concluded, therefore, that mobile fishing gear has the capability of altering structurally complex bottom communities, principally through the removal of biomass, and that such alterations will result in completely different bottom communities occupying those locations.

Mobile Fishing Gear Impacts on Benthic Community Processes

While the direct impacts of mobile fishing gear can be clearly delineated, the manner in which biogeochemical processes are altered can at present only be surmised. Using our knowledge of fundamental biological oceanographic processes, we can hypothesize the following consequences of repeated use of mobile fishing gear on marine sediment communities.

1. The decrease in structural complexity of harder bottom areas will result in a general decrease in biodiversity, which in turn will reduce the usefulness of these areas as nurseries for newly recruited fishery species. In addition, there will be biodiversity consequences in the form of a general decrease in energy cycling and community stability. Huston (1994) noted that "a large number of functionally analogous species may contribute to high stability and continuity of ecological and ecosystem function in the face of disturbances and environmental change" (p. 4).

2. The stirring and resuspension of muddy bottom sediments results in the destruction of burrows and tubes of species living infaunally. The resultant loss of biodiversity in these areas has produced a community with a few dominant species living primarily at the sediment - water interface. Since the most abundant of these, the brittle star *Ophiura sarsi*, is food for only a single species of flatfish, the American Plaice, the abbreviated food web of the muddy bottom can no longer support a diversity of fish species.

3. The homogenization of muddier sediments will result in a decrease in sediment-water interface area due to the collapse of burrows and destruction of tubes made by species dwelling within the sediment. Since 25-80% of the nutrients found in coastal and shelf waters are regenerated within the sediment, the loss of this interfacial area could have further consequences which are presently unknown.

4. The increased sediment resuspension already seen as a result of trawling on the continental shelf south of Georges Bank (Churchill 1989) and in Wilkinson Basin (Pilskaln, in prep.) results in a much thickened bottom nepheloid layer. Much of the higher quality food deposited to the sediment surface most likely will be further degraded as a result of this resuspension and settles to the bottom much lower in food value. There will, therefore, be a consequent reduction in overall biodiversity of these muddy bottom areas.

The Use of Mobile Fishing Gear as a Conservation Issue

To date, the regulation of fishing activities has been the exclusive responsibility of fisheries managers. In general, the use of varying kinds of fishing gear has been regulated on the basis of fishery catch data, in particular, trying to determine the influence of the gear on population parameters. Where issues of gear type rise to the level of dispute, the common response has been to look at the issue as a "gear conflict." This is especially true for mobile fishing gear, which until the mid 1980s was not used in the hard bottom areas of the Gulf of Maine. Rather, those areas were typically fished through the use of hook and line gear (which would have minimal impact on the bottom community). As roller gear was developed by the trawl fishery, those rough areas were no longer unfishable with mobile gear, and the long-line fishermen saw their fishing grounds produce progressively fewer fish. The response from the New England Fishery Management council has been to consider the complaints of the long-liners under the rubric of gear conflict, thus escaping the need to look at the habitat issues that might be involved.

Typically, only the fish harvesters have been considered to be stakeholders in this conflict. Because of the major changes that mobile fishing gear can bring to the bottom communities, however, anyone who is interested in the biodiversity of the sea must consider themselves as stakeholders in this debate. Consequently, the issue of gear type must be considered from a conservation point of view.

From a conservation perspective, there are some management options that could be practiced immediately that would allow the protection of certain particularly vulnerable habitats and not result in a complete ban on the use of mobile fishing gear (at least for now). These include:

1. Use a precautionary approach to management, which would result in minimizing the use of mobile fishing gear in structurally complex habitats.
2. Match fishing gear types to bottom habitat, thus minimizing long term impacts of all types of gear.
3. Establish "no trawling zones" around particular habitat types.
4. Take steps to educate the public about the nature of the sea bottom and its role in supporting the Gulf of Maine's fisheries as well its importance from the perspective of biodiversity.
5. Involve all sectors of society in the policy decision-making process, thus recognizing that all of us are "stakeholders" when it comes to the resources of the ocean.

References

Auster, P. J., R. J. Malatesta, and C. L. Donaldson. 1994. Small-scale habitat variability and the distribution of postlarval silver hake, *Merluccius bilinearis.* In *Gulf of Maine Habitat: Workshop Proceedings*, eds. D. Stevenson and E. Braasch, 82-86. ME-NH Sea Grant, UNHMP-T/DR-SG-94-18.

Auster, P. J., R. J. Malatesta, and S. C. LaRosa. 1995. Patterns of microhabitat utilization by mobile megafauna on the southern New England (USA) continental shelf and slope. *Marine Ecology Progress Series.* 127:77-85.

Auster, P. J., R. J. Malatesta, R. W. Langton, L. Watling, P. C. Valentine, C. L. S. Donaldson, E. W. Langton, A. N. Shepard & I. G. Babb. 1996. The impacts of mobile fishing gear on seafloor habitats in the Gulf of Maine (Northwest Atlantic): implications for conservation of fish populations. *Reviews in Fisheries Science.* 4: 185-202.

Bergman, M. J. N. and M. Hup. 1992. Direct effects of beam-trawling on macrofauna in a sandy sediment in the southern North Sea. *ICES Journal of Marine Science.* 49: 5-11.

Bradstock, M., and D. P. Gordon. 1983. Coral-like bryozoan growths in Tasman Bay, and their protection to conserve commercial fish stocks. *New Zealand J. of Marine and Freshwater Research.* 17: 159-163.

Buchholtz ten Brink, M. R., F. T. Manheim and M. R. Bothner. 1996. Contaminants in the Gulf of Maine: what's here and should we worry. In *The Health of the Gulf of Maine Ecosystem: Cumulative Impacts of Multiple Stressors*, eds. D. Dow and E. Braasch, 91-115. RARGOM Rept. 96-1.

Churchill, J. H. 1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. *Continental Shelf Research.* 9:841-64.

Craymeersch, J. A. 1994. Environmental impact of bottom gears on benthic fauna in relation to natural resources management of the North Sea. In *Environmental impact of bottom gears on benthic fauna in relation to natural resources management and protection of the North Sea*, eds. S. J. deGroot and H. J. Lindeboom, 209-236. Netherlands Institute for Sea Research, Report No. 11.

Dayton, P. K., S. F. Thrush, M. T. Agardy and R. J. Hofman. 1995. Environmental effects of marine fishing. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 5: 205-232.

deGroot, S. J. and J. M. Apeldoorn. 1971. Some experiments on the influence of the beam trawl on the bottom fauna. ICES C.M. 1971/B: 2 Gear and Behaviour Commission, 4 pp. (mimeo).

Ebeling, A. W. and M. A. Hixon. 1991. Tropical and temperate reef fishes: comparison of community structures. In *The Ecology of Fishes on Coral Reefs*, eds. S. J. deGroot and H.J. Lindeboom, 509-563. New York: Academic Press.

Eleftheriou, A. and M. R. Robertson. 1992. The effects of experimental scallop dredging on the fauna and physical environment of a shallow sandy community. *Netherlands J.of Sea Research,* 30: 289-299.

Gibbs, P. J., A. J. Collins and L. C. Collett. 1980. Effect of otter prawn trawling on the macrobenthos of a sandy substratum in a New South Wales Estuary. *Australian Journal of Marine and Freshwater Research.* 31: 509-516.

Gotceitas, V. and J. A. Brown. 1993. Substrate selection by juvenile Atlantic cod *(Gadus morhua)*: effects of predation risk. *Oecologia.* 93: 31-37.

Grimes, C. B., Able, K. W., Jones, R. S. 1986. Tilefish, *Lopholatilus chamaeleonticeps*, habitat, behavior and community structure in Mid-Atlantic and southern New England waters. *Env. Biol. Fish.* 15:273-292.

Hall, S. J. 1994. Physical disturbance and marine benthic communities: life in unconsolidated sediments. *Oceanography and Marine Biology: an Annual Review.* 32: 179-239.

Hall, S. J., D. Rafaelli and S. F. Thrush. 1994. Patchiness and disturbance in shallow water benthic assemblages. In *Aquatic Ecology: Scale, Pattern and Process*, eds. P. S. Giller, A. G. Hildrew and D. G. Rafaelli, 333-375. Oxford: Blackwell Scientific Publications.

Harris, A. N. and I. R. Poiner. 1991. Changes in species composition of demersal fish fauna of Southeast Gulf of Carpenteria, Australia, after 20 years of fishing. *Marine Biology.* 111: 503-519.

Heck, K. L. Jr. and R. J. Orth. 1980. Seagrass habitats: the roles of habitat complexity, competition and predation in structuring associated fish and motile macroinvertebrate assemblages. p. 449-464. In *Estuarine Perspectives,* ed.V.S. Kennedy, 449-464. New York: Academic Press.

Huston, M. A. 1994. *Biological Diversity: The coexistence of species on changing landscapes.* Cambridge: Cambridge University Press.

Kaiser, M. J. and B. E. Spencer. 1994. A preliminary assessment of the immediate effects of beam trawling on a benthic community in the Irish Sea. In *Environmental impact of bottom gears on benthic fauna in relation to natural resources management and protection of the North Sea,* eds. S. J. de Groot and H.J. Lindeboom, 87-94. Netherlands Institute for Sea Research, Report No. 11.

Kennicutt II, M. C., T. L. Wade, B. J. Presley, A. G. Requejo, J. M. Brooks and G. J. Deroux. 1994. Sediment contaminants in Casco Bay: inventories, sources, and potential for biological impact. *Environmental Science and Technology.* 28: 1-15.

Langton, R. W. and W. E. Robinson. 1990. Faunal associations on scallop grounds in the western Gulf of Maine. *J.of Experimental Marine Biology and Ecology.* 144: 157-171.

Langton, R. W., P. J. Auster, and D. C. Schneider. 1995. A spatial and temporal perspective on research and management of groundfish in the northwest Atlantic. *Reviews in Fisheries Science.* 3:201-229.

Laurenson, L. J. B., P. Unsworth, J. W. Penn and R. C. J. Lenanton. 1993. The impact of trawling for saucer scallops and western king prawns on the benthic communities in coastal waters off south-western Australia. Fisheries Department of Western Australia Fisheries Research Report No. 100, 93 pp.

Lough, R. G., P. C. Valentine, D. C. Potter, P. Auditore, G. R. Bolz, J. D. Neilson, and R. I. Perry. 1989 Ecology and distribution of juvenile cod and haddock in relation to sediment type and bottom currents on eastern Georges Bank. *Mar. Ecol. Prog. Ser.* 56:1-12.

Mayer, L. M., D. F. Schick, R. H. Findlay and D. L. Rice. 1991. Effects of commercial dragging on sedimentary organic matter. *Marine Environmental Research* 31: 249-261.

Messieh, S. N., T. W. Rowell, D. L. Peer and P. J. Cranford. 1991. The effects of trawling, dredging and ocean dumping on the eastern Canadian continental shelf seabed. *Continental Shelf Research.* 11: 1237-1263.

Nowell, A. R. M., P. A. Jumars and J. E. Eckman. 1981. Effects of biological activity on the entrainment of marine sediments. *Marine Geology.* 42: 133-153.

Oliver, J. S. and P. N. Slattery. 1985. Destruction and opportunity on the sea floor: effects of gray whale feeding. *Ecology.* 66: 1965-75.

Reise, K. 1982. Long-term changes in the macrobenthic invertebrate fauna of the Wadden Sea: are polychaetes about to take over? *Netherlands J.of Sea Research* 16: 29-36.

Rhoads, D. C., P. L. McCall and J. Y. Yingst. 1978. Disturbance and production on the estuarine seafloor. *American Scientist.* 66: 577-586.

Riesen, W. and K. Reise. 1982. Macrobenthos of the subtidal Wadden Sea: revisited after 55 years. *Helgolanders Meersuntersuchungen.* 35: 409-423.

Rolland, R. and T. Colborn. 1996. Transgenerational loss of function: a threat to biodiversity of marine ecosystems. *Bulletin of the Ecological Society of America*, suppl., 77 (3):380.

Sainsbury, K. J. 1991. Application of an experimental approach to management of a tropical multispecies fishery with highly uncertain dynamics. *ICES Marine Science Symposium.* 193: 301-320.

Sainsbury, K. J., R. A. Campbell and A. W. Whitelaw. 1993. Effects of trawling on the marine habitat on the North West Shelf of Australia and implications for sustainable fisheries management. In *Sustainable Fisheries Through Sustaining Fish Habitat*, ed. D. A. Hancock , 137-145. Australian Society for Fish Biology Workshop. Australian Government Publishing Service, Canberra.

Schnitker, D. S. 1986. Ocean basins with a past. *Explorations*. a Journal of Research at the University of Maine 3: 29-36.

Thomas, J. P. 1996. Status, trends, and health of wetlands: a 200-year overview and perspective. In *The Northeast Shelf Ecosystem: Assessment, Sustainability, and Management*, eds. K. Sherman, N. A. Jaworski and T. J. Smayda, 367-396. Oxford: Blackwell Scientific Publications.

Thrush, S. F., J. E. Hewitt, V. J. Cummings and P. K. Dayton. 1995. The impact of habitat disturbance by scallop dredging on marine benthic communities: what can be predicted from the results of experiments? *Marine Ecology Progress Series.* 129: 141-150.

Tupper, M. and R. G. Boutilier. 1995. Effects of habitat on settlement, growth, and postsettlement survival of Atlantic cod (*Gadus morhua*). *Can. J. Fish. Aquat. Sci.* 52:1834-1841.

Van Dolah, R. F., P. H. Wendt and N. Nicholson. 1987. Effects of a research trawl on a hard-bottom assemblage of sponge and corals. *Fisheries Research.* 5: 39-54.

Wahle, R. A. 1992a. Substratum constraints on body size and the behavioral scope of shelter use in the American lobster. *J. Exp. Mar. Biol. Ecol.* 159:59-75.

Wahle, R. A. 1992b. Body-size dependent anti-predator mechanisms of the American lobster. *Oikos*, 65:52-60.

Wahle, R. A. and R. S. Steneck. 1992. Habitat restrictions in early benthic life: Experiments on habitat selection and in situ predation with the American lobster. *J. Exp. Mar. Biol. Ecol.* 157:91-114.

Wheatcroft, R. A., P. A. Jumars, C. R. Smith and A. R. M. Nowell. 1990. A mechanistic view of the particulate biodiffusion coefficient: step lengths, rest periods and transport directions. *J. of Marine Research.* 48: 177-207.

White, H. H. and A. Robertson. 1996. Biological responses to toxic contaminants in the Northeast Shelf Large Marine Ecosystem. In *The Northeast Shelf Ecosystem: Assessment, Sustainability, and Management*, eds. K. Sherman, N. A. Jaworski and T. J. Smayda, 259-283. Oxford: Blackwell Scientific Publications.

White, P. S. and S. T. A. Pickett. 1985. Natural disturbance and patch dynamics: an introduction. In *The Ecology of Natural Disturbance and Patch Dynamics*, eds. S. T. A. Pickett and P.S. White, 3-13. Academic Press.

Witman, J. D. 1987. Subtidal coexistence: storms, grazing, mutualism, and the zonation of kelp and mussels. *Ecological Monographs.* 57: 167-187.

Yevich, P. P. and C. A. Barszcz. 1977. Neoplasia in soft-shell clams (*Mya arenaria*) collected from oil-impacted sites. *Annals of the New York Academy of Sciences.* 298: 409-426.

Fisheries-Induced Biological Changes to the Structure and Function of the Gulf of Maine Ecosystem

Robert S. Steneck
University of Maine

"The Gulf of Maine constitutes one of the most important fishing areas of the eastern coast of North America, both from the abundance of fish which resort to it and its close proximity to numerous large and enterprising fishing ports."
(Collins and Rathbun 1887)

"It is probable that no other fishing area equaling this in size or in productivity exists anywhere else in the world..."
(Rich 1929)

"Groundfish stocks have been depleted"
(Maine's Commissioner of Sea and Shore Fisheries Annual Report 1949).

Abstract

Atlantic cod and other large predatory groundfish were important components of near shore marine habitats in the Gulf of Maine for over four thousand years. They were harvested over most of that time by hook and line through the 1920s. In the 1930s otter trawls and other technological improvements allowed for the efficient harvesting of spawning stocks and by the end of the 1940s groundfish stocks in coastal zones were said to be depleted. Studies conducted over the past 109 years document this rapid decline of coastal fishing grounds and changes in average body size of cod. Several decades later, harvesting caused the decline of the offshore groundfish on Georges Bank. Dominant fish predators were replaced by commercially less important species, such as sculpins, in coastal zones and dogfish and skate on Georges Bank. Today large predatory finfish are functionally absent from vast regions of the Gulf of Maine. This loss of the top trophic level for benthic systems may have fundamentally altered food webs, with lobsters, crabs and sea urchins increasing in abundance in coastal zones. Fisheries-induced changes there have continued with the sequential targeting of species at lower trophic levels. The recently developed industry for herbivorous sea urchins has caused significant declines in their abundance and has resulted in increases in kelp and other macroalgae. This may increase productivity, habitat and the recruitment potential for some species in coastal zones. If true, such cascading changes to both the structure and function of the Gulf of Maine ecosystem may make predictions difficult or impossible.

Introduction, Approach and Rationale

Fisheries exploitation can alter natural marine ecosystems more rapidly and at a larger scale than most other human-induced effects. This has been demonstrated for many areas of the world (Aronson 1994, Hughes 1994) and is particularly evident in the Gulf of Maine, where centuries of escalating fishing pressure has taken a toll on targeted populations. This paper presents evidence of alterations in the Gulf of Maine ecosystem's structure by documenting changes in the distribution, abundance, and body size of its dominant species. It also considers how changes in diversity, structure and function of food webs may affect other components of the ecosystem. Ecosystem function is modified when dominant predators are exploited because changes in their abundance can have cascading influences on prey populations and lower trophic levels.

Human-induced changes to the Gulf of Maine ecosystem is likely to be most evident in coastal zones because of their proximity to population centers. These patterns extend throughout the system but the temporal and spatial resolving power becomes weaker. In order to control for regional variation, much of the time-series research which is cited here will apply to the central coast of Maine. This avoids problems lurking in discussions of temporal changes between areas that are, and always have been, oceanographically different. Also, continuity in data for recent stock assessments is facilitated by working within coastal waters of a single state that comprises the majority of coastal waters of the Gulf of Maine.

Harvesting has traditionally focused on higher-order predators because they have high food and economic value. Such predators also have a disproportionately greater impact on the rest of ecosystem because of their role as predators. Examples of single top predators or "keystone species" influencing community structure are well known for many marine ecosystems (Paine 1969, Simenstad et al. 1978) but more recently the research focus has shifted to consider the result of a functional loss of an entire trophic level (e.g., Hughes 1994, Steneck 1994). Therefore this discussion will address the human impacts on biological populations that potentially control the trophic structure of food webs of the Gulf of Maine.

In recent decades, the landed value of fisheries resources in the Gulf of Maine has shifted from top-predator groundfish such as Atlantic Cod, to middle predators such as lobsters and most recently to herbivorous sea urchins, which in 1994 was the second most valuable fishery in the state of Maine. Collectively, these groups make up much of the top-grossing economic resources of the Gulf of Maine and are a significant component of coastal food webs of the Gulf of Maine. Thus I will pursue the central question: have humans significantly altered the structure and function of these food webs? To address it, we need to consider how the system was structured in the past, how rapidly (if at all) it changed, and what evidence for and consequences of that change are apparent today.

Stability and Change of Large Predatory Fish Over the Past Four Thousand Years

Long-term Dominance of Coastal Groundfish

The first clear evidence of human exploitation of marine resources of the Gulf of Maine is found in middens of people from the Late Archaic period between forty-five hundred and thirty-eight hundred years ago (Borque 1996). Evidence of long-term exploitation of gadids determined to be Atlantic cod is found at numerous coastal sites in Maine. Large cod vertebra were taken from sites occupied over four thousand years ago (Borque personal communication). Cod was still the dominant fish species found in middens dated from twenty-five hundred to five hundred years ago where it comprised over 80% of the excavated bone mass (Figure 1, Carlson 1986). Evidently, large cod and other fish were exploited for literally thousands of years in coastal regions of the Gulf of Maine.

When the first Europeans explored the Gulf of Maine, it was the abundance of large fish that impressed them (Rosier 1606). Vespucci marked the northern half of his 1526 map of the New World "*Bacallaos* " which is Portuguese for "land of the codfish." In 1602, Bartholemew Gosnold named Cape Cod for the myriad fish that "vexed" his ship. Captain John Smith reported three

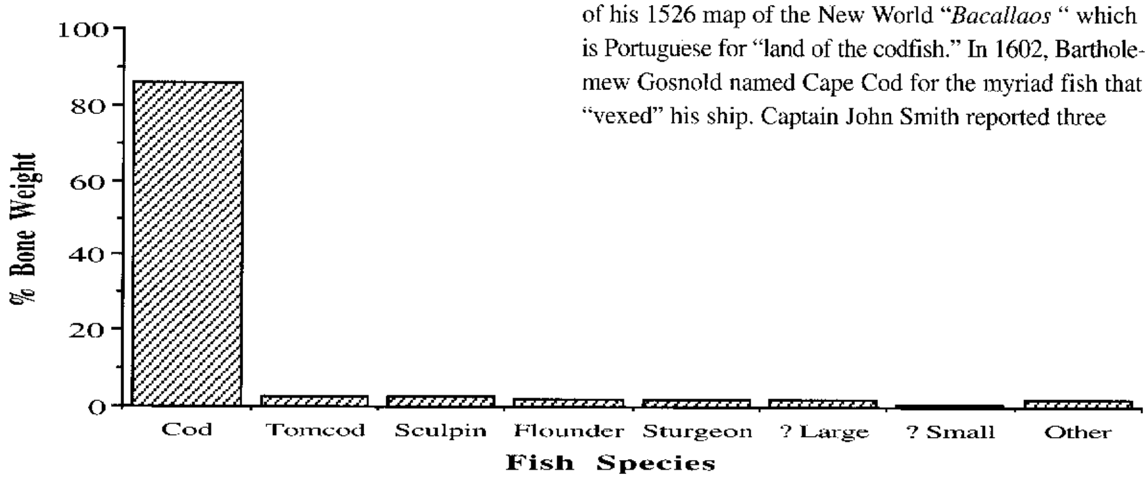
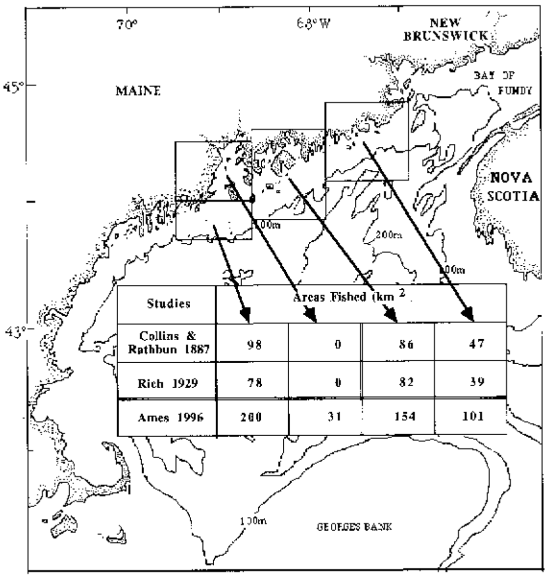


Figure 1. Abundance of fish bones found in middens from the Boothbay Harbor region of Maine 500 to 2500 years ago (from Carlson 1986).

important facts in 1616: 1) that cod were abundant along the coast, 2) that native Americans already knew this, and 3) the cod in Maine were two to three times larger than those found elsewhere in the new world (Smith 1616). In the early 1600s, seafood from the Gulf of Maine had a larger share of the market in Europe than it does today (Caldwell 1981). At that time, 10,000 men were employed fishing for cod in New England (Caldwell 1981), and by the 1880s, three times that number were employed in Nova Scotia alone (Barnard 1986). Late nineteenth century advances in ships and harvesting practices greatly increased harvesting effectiveness. This may have been the zenith of the codfish industry. By any measure of stability (see Connell and Sousa 1983), large predatory fish such as Atlantic cod were a stable component of coastal zones in the Gulf of Maine ecosystem.

Recent and Rapid Changes in Harvesting Technique, Fishing Grounds, and the Abundance and Size of Predatory Fish

Since the 1800s, cod and other large-bodied predatory fish targeted by fishermen declined in abundance and size until they were virtually eliminated from coastal habitats. This decline is evident in charts of coastal fishing grounds published over the past century. Since these charts were developed using the same interview techniques over identical areas, they provide a means for making quantitative comparisons (Figures 2, 3). The nearshore fishing grounds mapped in the 1800s (Collins and Rathbun 1887, Watson 1996) began to shrink by the 1920s while some new grounds were fished (Rich 1929, Figures 2, 3). From the 1930s to 1960s, the old grounds were significantly reduced and new inshore grounds and "up-estuary" (Figures 2, 3) were being exploited. This, however, was short lived, and today there is no significant inshore fishery (Conkling and Ames 1996).



Studies	Areas Fished (km 2)			
Collins & Rathbun 1887	98	0	86	47
Rich 1929	78	0	82	39
Ames 1996	200	31	154	101

Figure 2. Changes in areal extent of fishing grounds in four rectangular regions in coastal zones of the Gulf of Maine over the past century. The tabulated areas fished (km ^{2}), from left to right, represent outer Penobscot Bay, inner Penobscot Bay (i.e., "up estuary"), Mt. Desert region and Washington County, Maine. Chart compilation by Watson (1996), [used published (Collins and Rathbun 1887 and Rich 1929) and unpublished charts (Ames 1996) from which area determinations were made (this study)].

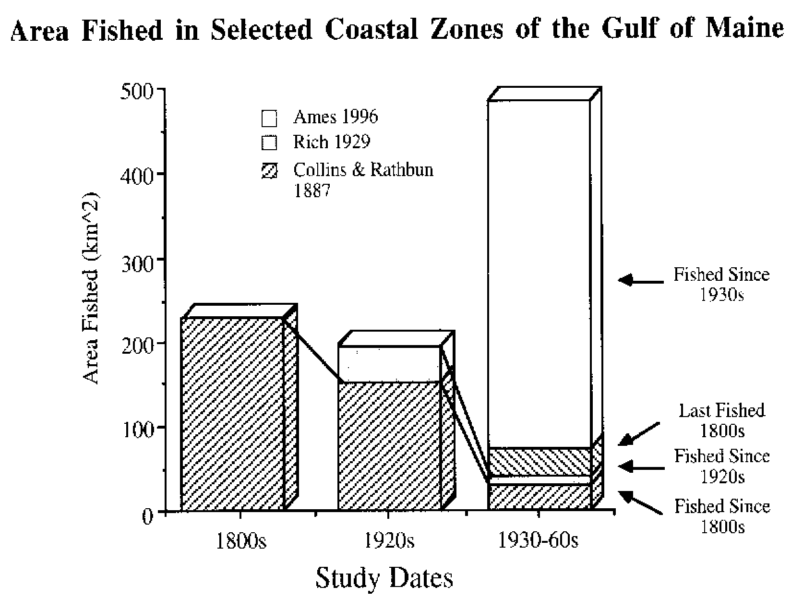


Figure 3. Changes in areas fished since 1800s for selected areas of the Gulf of Maine (data as determined for rectangles in Figure 2). Note that fishing grounds identified in the 1880s decline slightly by the 1920s but dramatically after that. New grounds increased slightly in the 1920s but exploded in the following three decades as fishing practices changed (Figure 4).

Coincident with the most recent rapid decline in fishable stocks along the coast was a change in fishing methods. Hooks carved from deer bones were used for thousands of years prior to European interests in the fish stocks of the Gulf of Maine. Hook and line fishing continued as the predominant means of harvest through the 1920s (Figure 4). In the 1930s, vessels capable of trawling and refrigerating otherwise difficult to catch groundfish, and preserving spawning fish, represented a radical departure in the way fish were harvested. During the past few decades, hooks were rarely used for the commercial harvest of groundfish.

Estimating the abundance of fishes based on fisheries data is difficult, especially as fishing technology and methods change. However the hook and line harvest may be comparable over time. Since it is likely to be effective only where dense aggregations of feeding fishes occur, abundance estimates over the same general areas, over a long period of time, should provide evidence of change. Until the advent of vessels capable of dragging otter trawls and of refrigeration, breeding aggregations were avoided because of their poor market value and difficulties in catching and bringing those fish to market (J. Wilson personal communication, Watson 1996). However once those technological hurdles were cleared, massive landings of spawning groundfish in near-shore coastal zones occurred. This change in fishing method and targeting spawning individuals was coincident with the extirpation of coastal groundfish stocks. The annual assessment of coastal groundfish stocks by Maine's commissioner of Sea and Shore Fisheries (which later became Maine's Department of Marine Resources) documented this rapid decline. In 1918 stocks were said to be "*flourishing*", in 1934 the commissioner stated "*most species of groundfish are growing scarcer*", in 1949 the commissioner concluded that "*groundfish stocks have been depleted*" (Conkling and Ames 1996).

In addition to declining abundances, average fish body size also steadily dropped. In 1895 a 96 kg (= 211.25 lb) cod was caught on a long-line off the Massachusetts coast (Bigelow and Schroeder 1953) and many ranging in size from 45-73 kg (100 - 160 lb) were described in the 1800s (Goode 1884). However since the turn of the century, fish exceeding 45 kg have become exceedingly rare (Bigelow and Schroeder 1953). The decline in average body size of cod in coastal zones is particularly dramatic over the past forty years (Figure 5).

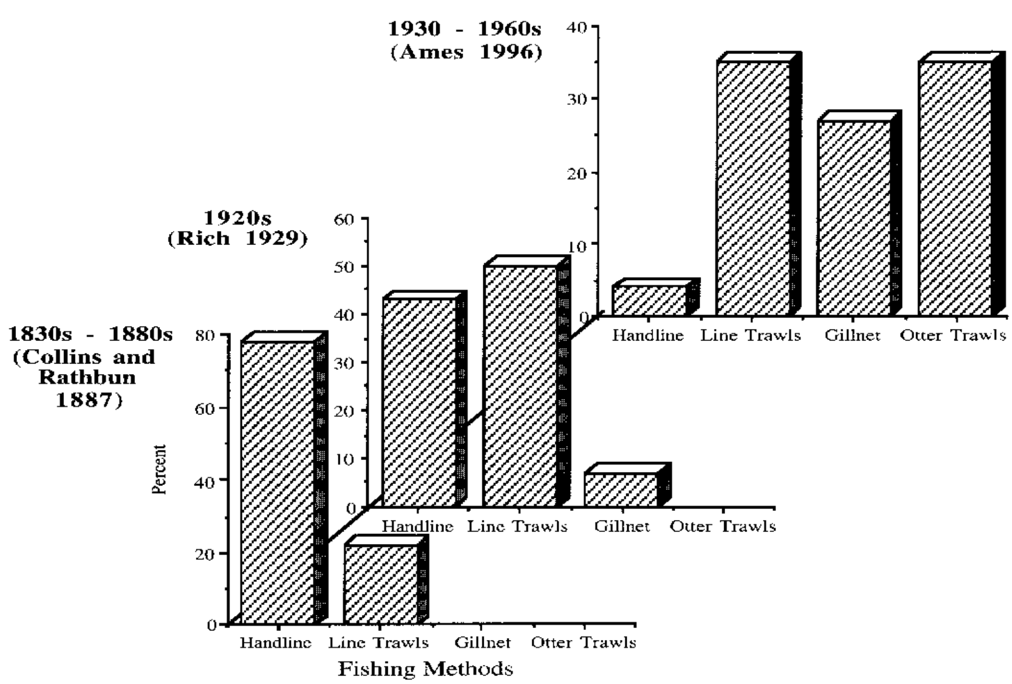


Figure 4. A comparison of fishing methods for identical areas (rectangles on map in Figure 2) over time. Of 138 identified fishing areas, the 9 that were fished continuously over the past century were used in this analysis. Data from Watson (1996).

Shifts in Dominance: Replacement of Large Predatory Fish by Commercially Less Important Species

Large predatory fish were ubiquitous in coastal zones through at least the 1920s but are rare or absent today. In the 1920s, a compilation of 147 coastal fishing grounds found over 90% of them yielded Atlantic cod (Figure 6; Rich 1929) and five of the six most commonly harvested fish (Figure 6) are among the six largest species of benthic fishes found in the Gulf of Maine (Figure 7). With the virtual extirpation of large-bodied

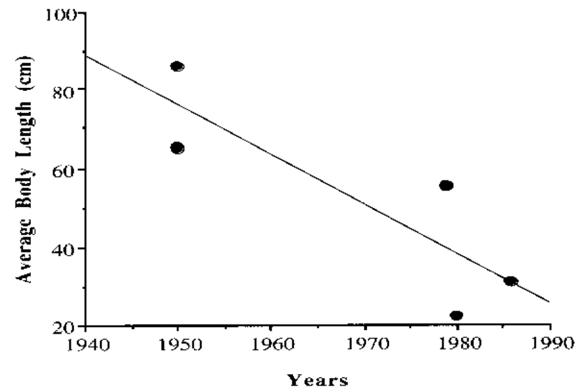


Figure 5. Decreasing average size of cod in coastal regions of Maine. Data from Bigelow and Schroeder 1953, Hacunda 1981, Ojeda and Dearborn 1989.

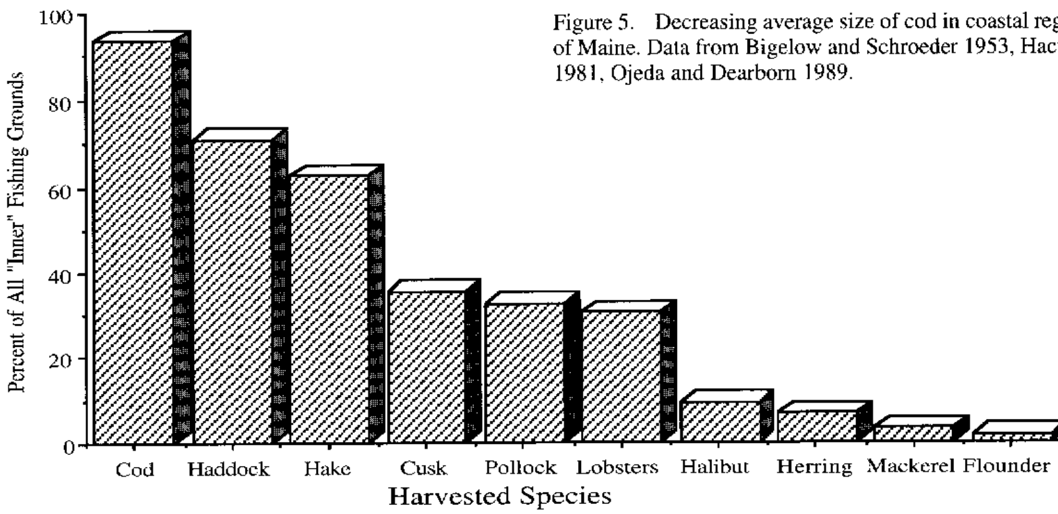


Figure 6. Predominant coastal fisheries species identified in 147 coastal ("inner") fishing grounds during the 1920s (Rich 1929).

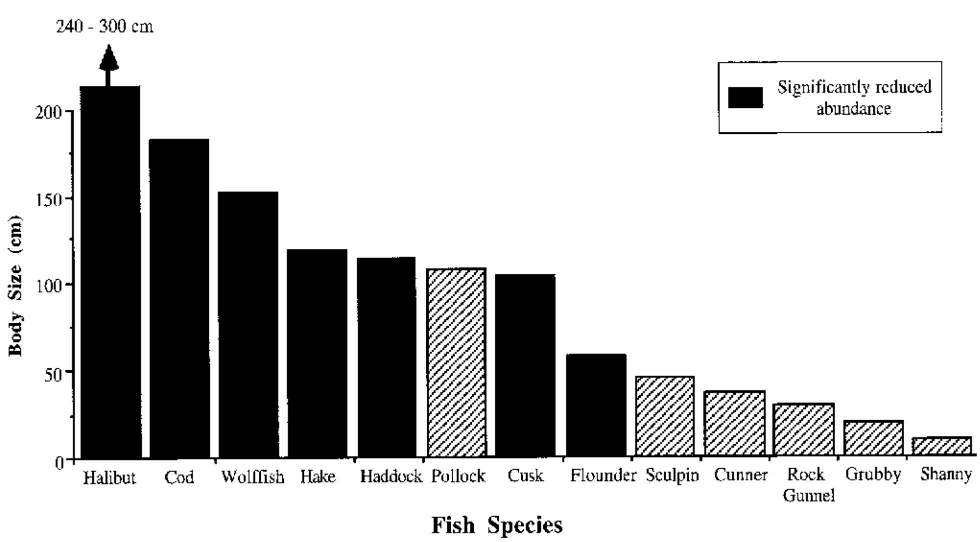


Figure 7. Maximum body sizes (total length) of dominant demersal or benthic fish predators in the Gulf of Maine. Data from Bigelow and Schroeder (1953) and Scott and Scott (1988).

groundfish from coastal zones, the dominant fish predators today are all relatively small (Figure 8). Today, small-bodied sculpins (grubbies, short-horned and long-horned sculpins), rock gunnel, shanny and cunner are the dominant fish predators in coastal zones of Maine (Malpass 1992, Witman and Sebens 1992). In hundreds of hours of videos at five coastal locations (Jonesport, Mt. Desert, Pemaquid, Maine; Rye, New Hampshire; and Nahant, Massachusetts) no cod or other large-bodied gadids were observed (Malpass 1992, Steneck et al. 1995, Vadas and Steneck 1995). Today, the predominant coastal fisheries species for the areas reported by Rich (1929; Figure 6) are lobsters and sea urchins (Maine's Department of Marine Resources).

The fisheries-induced decline of groundfish such as Atlantic cod continued throughout the Gulf of Maine but near collapse of the stock occurred much later in offshore areas such as Georges Bank (Figure 9). It is

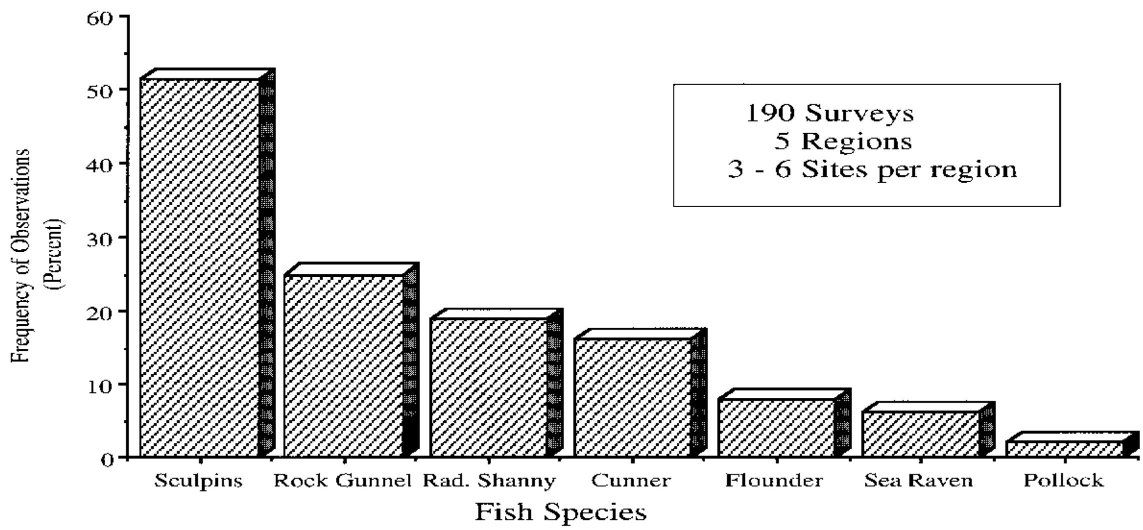


Figure 8. Abundance of fish predators in coastal benthic surveys taken in 1989 (Malpass 1991). The five study regions were located in Maine near Jonesport, Mt. Desert, Pemaquid, and in Rye New Hampshire and Nahant, Massachusetts. Each is more than 50 km apart; within each region three to six study sites were at least one km apart. Surveys were conducted by scuba diving and recording all fish within 10 m belt transects at a depth of 10 m.

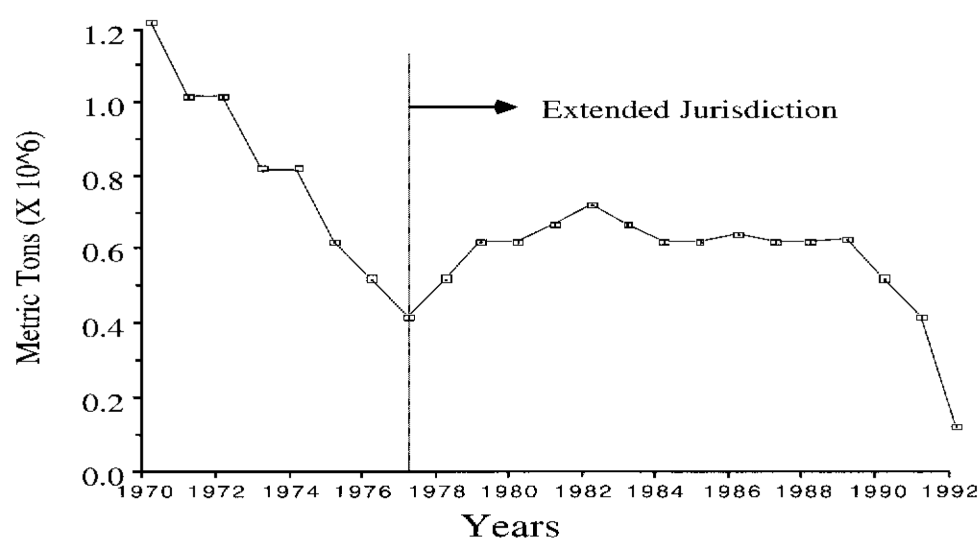


Figure 9. Landings of Atlantic cod from 1970 to 1992 (from Sinclair and Page 1995). The monotonic decline from 1970 to 1977 was temporarily reversed when jurisdictional economic zone boundaries were extended in 1977 as part of the Magnuson Act. The decline continued in the 1990s once home country fishing fleets developed in the region.

widely believed that the decrease in finfish abundance resulted from harvesting (e.g., Brown et al. 1978, Mayo et al. 1992, Myers et al. 1997). Because the offshore decline in groundfish (Figure 9) occurred much later than did the coastal decline, fishing pressure rather than oceanographic processes are generally believed to be the cause. In fact, Frank and Leggett (1994) suggested that "*the dramatic decline of cod throughout the North Atlantic may be the result of systematic overexploitation of spawning concentrations.*" Some significant regulatory changes are in effect experiments that demonstrate fishing impacts. For example, the steady decline in cod abundance on Georges Bank and the outer continental shelf from 1970 to 1977 stopped abruptly and reversed when the Magnuson Act extended jurisdiction of the exclusive economic zone around the United States (Figure 9; Hennemuth and Rockwell 1987). That act halted fishing from all non-United States fishing vessels allowing stocks to recover slightly and stabilize for over a decade until the United States fleet responded to the recently vacated fishing grounds. As fishing pressure escalated, stock decline resumed and accelerated from 1989 to 1992 Sinclair and Page 1995). Currently, parts of Georges Bank are under protective closures to stem further losses of groundfish. This example is widely cited as evidence of human impacts on cod populations (e.g., Mayo et al. 1992, Sinclair and Page 1995).

With the decline in groundfish on Georges Bank, there was a change in species composition. As discussed above for coastal zones, Georges Bank saw large commercially important fish get replaced by smaller, less commercially-important species. For example, gadids such as cod and haddock dominated fish stocks in the 1960s, but that area was dominated by skates and dogfish by the late 1980s (Figure 10, Sherman 1991, Mayo et al. 1992). My recent submersible research on Georges Bank during the summers of 1993 - 1995 observed very few gadids at 200 m depth. Thus the landings data (Figure 9) conforms with what even casual observers see in those habitats.

Changes to Food Webs Resulting from Loss of Large Predatory Fish

Extant Refugia for Large Predatory Fish: Laboratories to Study Their Impact

The relative absence of large predatory finfish in coastal zones today makes examination of their impact difficult. However, there are a few populations of large predatory groundfish located in relatively shallow-water refugia where their impact can be studied. One such refuge is Cashes Ledge, a submarine rock island 130 km offshore that shallows to 15 m from the surface. It has kelp and other coastal community characteristics (Vadas and Steneck 1988) but during the late 1980s and early 1990s it still had significant populations of large predatory fish such as cod, pollock and wolffish (Figure 11, Witman and Sebens 1992 — next page). The area was avoided as a fishing grounds for centuries. Collins and Rathbun (1887) reported "*Cashes Ledge. — This is not now a very important fishing-ground...*" by the 1920s, Rich (1929) reported it was "*furnishing... its quota* [of groundfish]*... in increasing volume... The principal fishing on these grounds is for cod, haddock hake and cusk...*" However, the abrupt vertical rise of Ammen

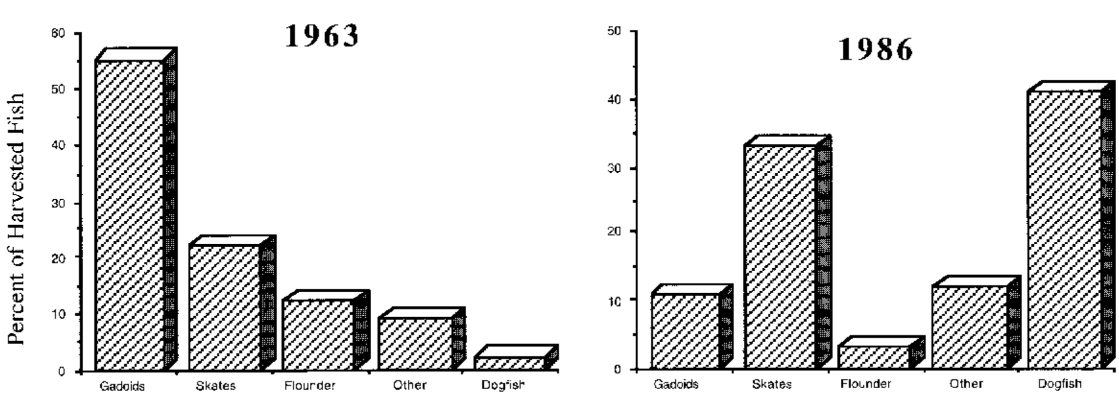


Figure 10. Changes in the proportion of harvested fishes on Georges Bank (from Sherman 1991).

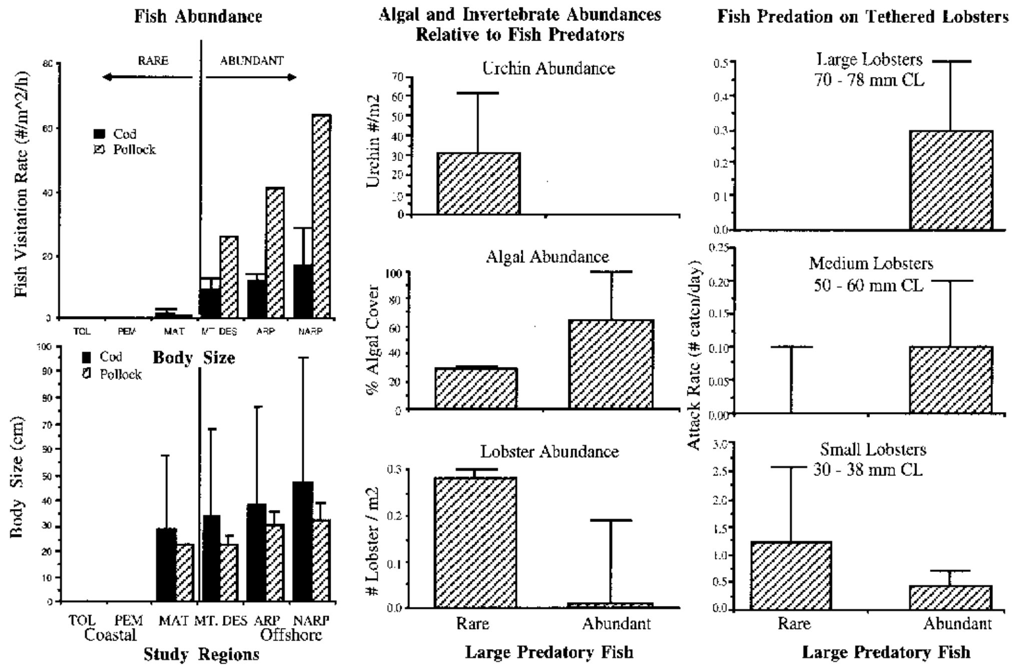


Figure 11. Geographic patterns of large predatory fishes at the Cashes Ledge region (i.e., Ammen Rock Pinnacle "ARP" and North Ammen Rock Pinnacle "NARP"), islands of Matinicus ("MAT") and Mt. Desert Rock ("MT.DES") with coastal sites (Thread of Life, "TOL" and Pemaquid Point, "PEM"). Fish abundance and body size was determined with in situ videos (left two graphs). Sea urchin, algal and lobster abundances (middle three graphs) were quantified with quadrat sampling (three sites where fish were rare and three sites where fish were abundant were respectively pooled). Fish predation was quantified using tethered lobsters of small, medium and large size classes (right three graphs) with simultaneous video recordings to identify predators. Error bars represent one standard deviation in all cases.

Rock Pinnacle of the Cashes Ledge complex was probably exceedingly difficult to fish since anchoring was difficult and trawling impossible without recently-available rock-hopping trawling gear. Since experiments remained intact without trawling damage on Ammen Rock Pinnacle from 1984 through 1991, trawling could not have occurred on the pinnacle summit during that period at least. Thus, this small pinnacle was a refuge for large predatory fishes and it became a research laboratory to examine predation by those fishes.

Quantitative comparisons of large predatory fish abundance were accomplished using video cameras trained on marked meter square areas (methods described in Witman and Sebens 1992). Approximately equal observation periods for six sites revealed three sites where large predatory finfish (e.g., cod and pollock) were abundant and three sites were they were rare (Figure 11 left). *In situ* quadrat surveys quantifying dominant benthic organisms were conducted at each site and data pooled according to sites where large predatory fish were abundant and where they were rare.

Lobster and sea urchins were rare at sites dominated by large predatory fish (Figure 11 middle). Tethering studies show attack rates on lobsters were much greater there (Figure 11 right). Further, algal abundances, particularly kelp, were significantly greater at sites devoid of urchins. This is undoubtedly due to the controlling influence sea urchins have on kelp abundance (e.g., Steneck et al. 1995, Vadas and Steneck 1995). Steneck et al. 1995 showed that fish attacks on tethered sea urchins were confined to sites where large predatory fish were abundant. In particular, large urchins (i.e., 70 - 80 mm test diameter) suffered heavy mortality from fish only at the offshore, predator-abundant sites. Simultaneous research measuring in situ rates of herbivory (using an herbivory bioassay which quantifies the rates at which 2.5 X 15 cm strips of kelp are consumed; Steneck et al. 1995) found that urchin abundance accounts for most of the community-wide rates of herbivory (also see Steneck and Dethier 1994). Thus urchin grazing is an important regulator of kelp abundance (Figure 11, Steneck et al. 1995).

Cascading Consequences of Altered Food Webs

Coastal marine landscapes have changed as a result of the loss of the large predatory finfish (Figure 12). Today, mobile benthic invertebrates (e.g., Menge and Sutherland 1987) and small, commercially-unimportant finfish (Figure 8; Wahle and Steneck 1992, Malpass 1992) are abundant and appear to be the most important fish predators in coastal zones of the Gulf of Maine. Altered abundances, due to direct harvesting losses and population release from predatory control, are evident at several levels in coastal food webs (Figure 12). Some of these changes redirected fishing effort to lower trophic levels, which has had numerous consequences affecting nearly all trophic levels.

Body size is a prime determinant of outcome in predator-prey interactions. Therefore, as fish predator size declines, prey populations will increase. Variations in lobster landings over the past century may reflect changes in large predatory finfish (Figure 13). Lobster landings were high in the late 1800s and declined as lobstering expanded. Early in the lobster fishery the average harvested size of lobsters was large. One report

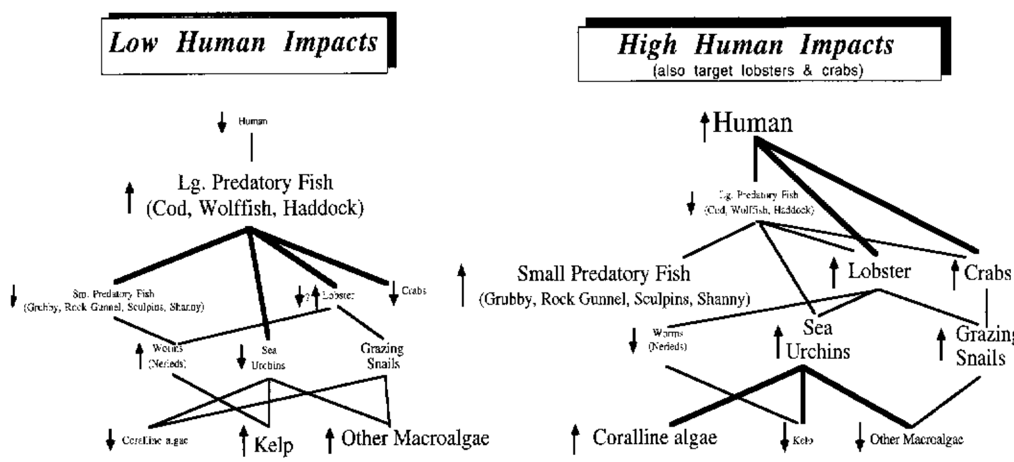


Figure 12. Hypothesized food web changes in coastal zones of the Gulf of Maine resulting from human impacts. Strong interactions (sensu Paine 1980) are indicated by heavy lines. Arrows and font size indicate relative abundance and/or importance to the system.

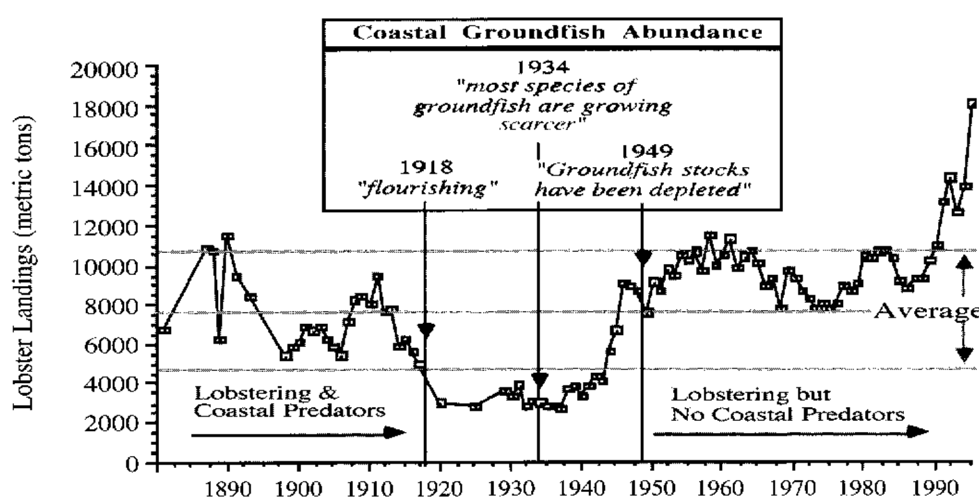


Figure 13. Lobster landings and coastal groundfish abundance in Maine. Average landings since 1880 (± one standard deviation) are indicated by dotted lines (data from Maine's Department of Marine Resources). The record low landings occurred from 1920 through 1940s and the record high landings have occurred since 1990. Coastal groundfish abundances were assessed annually by Maine's commissioner of Sea and Shore Fisheries (later to become the Department of Marine Resources).

from the 1860s indicate that "*Lobsters weighing twenty to twenty-five pounds were often taken... four or five pound lobsters... were so common that two pound lobsters were taken and thrown overboard.*" (In a letter from J. P. Baxter 1918 reported in Martin and Lipfert 1985). Very large lobsters were probably always relatively safe from predation even when large cod were patrolling coastal zones. As lobstering intensified, average body sizes decreased. Rathbun (1887) stated: "*Why do we not get larger lobsters? Must be, we catch them faster than they can grow; the smaller the lobsters we retain, the smaller will they become in the future.*" As lobster populations shifted to smaller size, a larger percent of the remaining lobster population may have fallen prey to the large predatory fish. This would not only account for the steady decline in lobster abundance from 1890 to 1920 but also the sharp increase in the 1940s after finfish stocks had "*been depleted*" (Figure 13).

Today, lobsters are vulnerable to predation only very early in life from small, commercially unimportant predatory fishes (Figures 8, 11; Wahle and Steneck 1992). Tethering results of somewhat larger but still preharvestable lobsters showed that they were vulnerable to predation only in rare locations where large predatory fish were still present (Figure 11). They also indicated that adult crab, lobsters and sea urchins live today in coastal habitats without significant threats from predators (Figure 11; Wahle and Steneck 1992, Steneck et al. 1995, Vadas and Steneck 1995). The absence of predators probably allows more lobsters to live in shelter-poor habitats than was possible when predators were abundant. This expansion of habitable area for lobsters may have contributed to the currently thriving lobster industry which, in recent years, has repeatedly exceeded its previous record harvest, set in the 1880s (Acheson and Steneck 1997, Steneck 1998).

Large fish predators may also have limited sea urchin populations. With the decline of coastal predators, urchin populations may have expanded their populations (Figure 14, note increase in urchins from 1975 to 1985). Dense urchin populations denuded kelp from vast coastal areas (Figure 14, note decrease in kelp from 1975 to 1985) thereby reducing coastal productivity and habitat structure for other organisms (e.g., Bologna and Steneck 1993). Sea urchins have recently become a targeted species for their highly valued roe (Figure 15). Where urchin harvesting has been intense, urchin population densities have dropped (Figure 14) and kelp beds have returned (Steneck et al. 1995, Figure 14).

As urchin population densities declined from 1983 to 1994, measured rates of herbivory decreased (Figure 16 left). With lower herbivory, kelp abundance dramatically increased (Figure 16 right). The direct relationship between urchin abundance, measured rates of herbivory and changes in kelp abundance (Figures 14, 16) suggest that the green sea urchin is the primary benthic herbivore in coastal systems, and that changes in their abundance controls the entire herbivore trophic level (Figure 17).

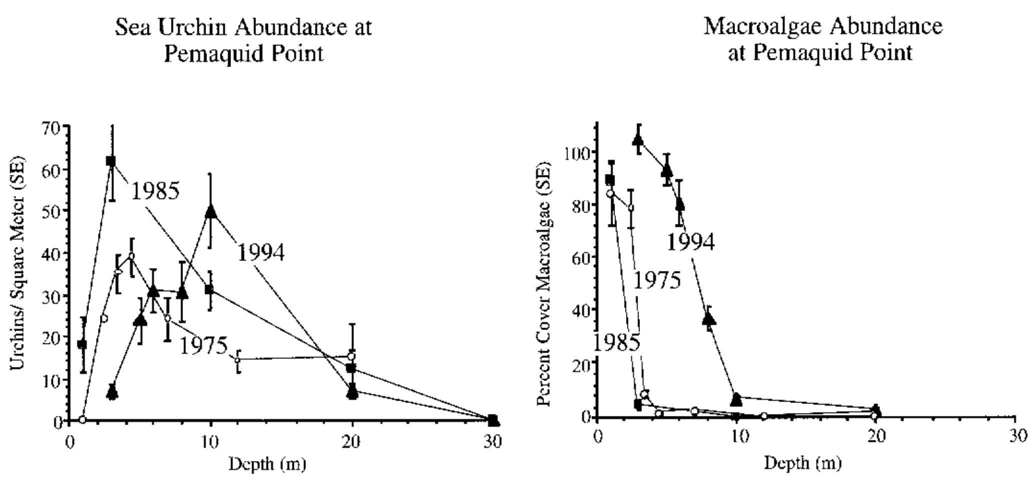


Figure 14. Depth and abundance trends in sea urchins (left) and macroalgae (i.e., kelp, right) at Pemaquid Point, Maine (after Steneck et al. 1995). Note the rapid decline in urchin abundance and increase in kelp abundance in shallow zones as urchin harvesting escalated in the 1990s (Figure 15).

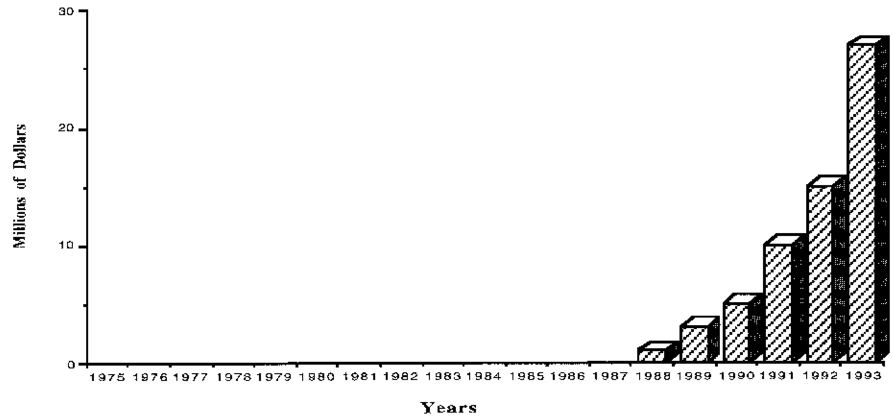


Figure 15. Trend in Maine sea urchin harvest (Maine DMR).

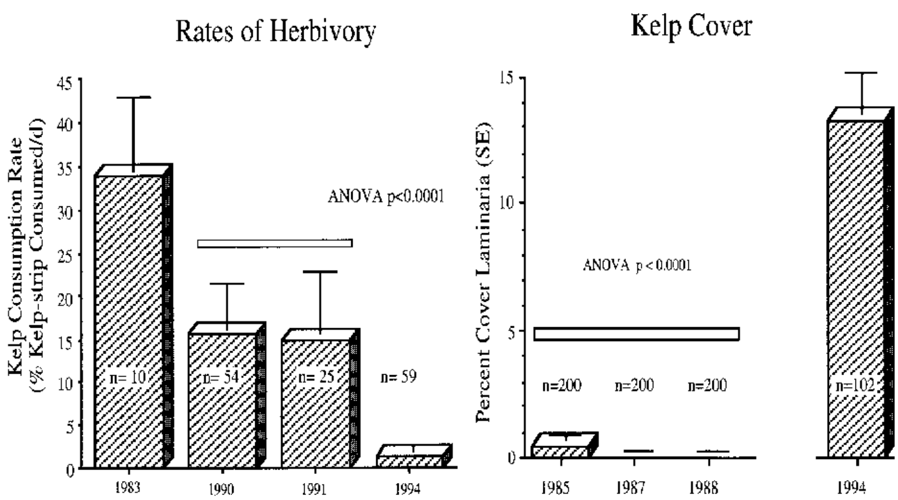


Figure 16. Temporal trends in rates of herbivory (left) determined using the kelp strip herbivory bioassay (methods in Steneck et al. 1995) and in percent cover (using quadrat sampling). Variance expressed as standard error (SE) with vertical line from each bar. All work was conducted near Crow Island Maine (near TOL site in Figure 11, Steneck et al. 1995). n = number of kelp strips, horizontal bars indicate samples among which no significant differences were found using analysis of variance (ANOVA at p = .01).

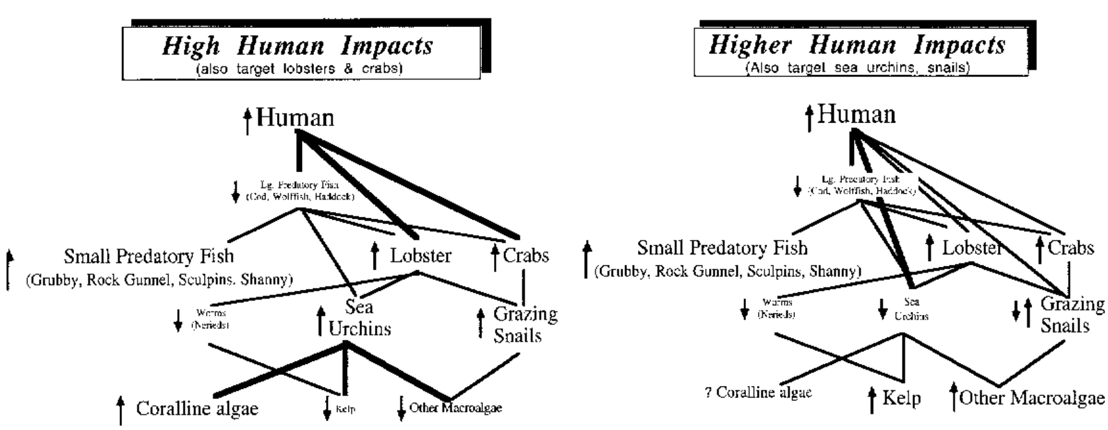


Figure 17. Hypothesized continued changes to coastal food webs for coastal zones of the Gulf of Maine resulting from human impacts. Notations as in Figure 12.

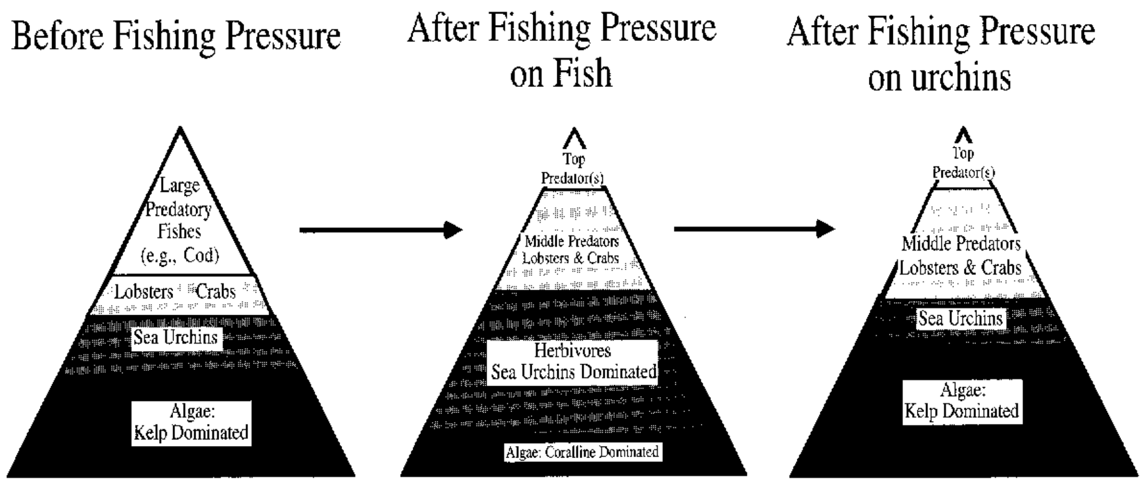


Figure 18. Changes in trophic-level abundance for coastal food pyramids of the Gulf of Maine as fishing pressures escalated. The area of each shaded pattern qualitatively represents biomass.

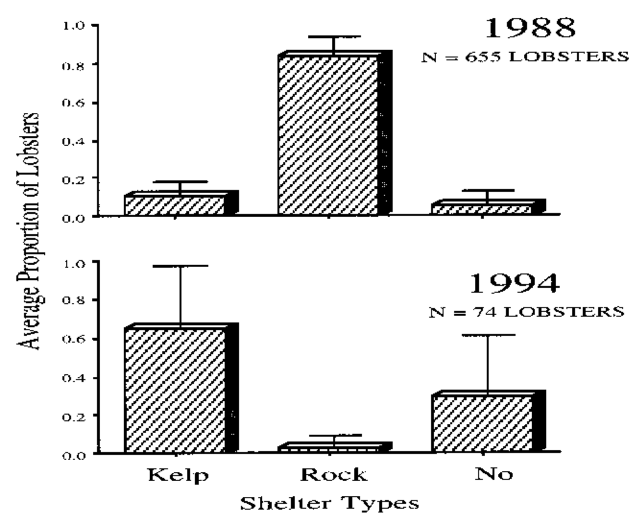


Figure 19. Changes in lobster habitat use concurrent with changes in kelp abundance, resulting from reduced rates of herbivory (Figure 16) following harvesting for sea urchins (Figure 15). Data are for precisely the same benthic survey sites at Crow Island, Maine (see Figure 16).

All of this suggests that food webs are changing to due the cascading effects of harvesting. Food webs prior to intense fishing activity (Figure 18) suggests coastal zones were probably dominated by large predatory fish and an abundance of kelp (Vadas and Steneck 1995, Steneck 1995). With increased resource exploitation by humans, top predators were removed, allowing for an expansion of middle predatory such as lobsters crabs and sea urchins. Targeting lobsters has not yet reduced their abundance (Figure 13) but the same cannot be said for sea urchins. Since the green sea urchin is the principle member of the herbivore trophic level, reductions in its abundance causes dramatic and immediate change to kelp populations and to coastal food webs in general (Figure 18 right).

The dramatic increase in kelp (Figures 14, 16) immediately following the localized extirpations of sea urchins has caused numerous other changes to coastal systems. This increase of the largest benthic producers in the western North Atlantic may increase coastal productivity. Recently, large increases in macroalgal detritus has been observed. Kelp beds baffle and reduce wave action and hosts numerous epiphytic and epizoic organisms (Duggins et al. 1990). Organisms such a crustose coralline alga, *Clathromorphum circumscriptum*, which can be overgrown and thus out-competed by macroalgae (Steneck 1986) is the preferred food for the limpet, *Tectura testudinalis* (Steneck 1982). With the expansion of macroalgae, this coralline and its dependent limpet have declined in abundance (Steneck unpublished data). Lobster habitat use has also changed. At a site where lobsters predominantly occupied rock shelters during the 1980s, a clear shift to kelp shelter use was observed (Figure 19). Expanded kelp beds may present a significant expansion of lobster habitat in coastal zones (Bologna and Steneck 1993).

Kelp and other macroalgae are nursery grounds for some large predatory finfish (Levin 1991, 1994, Carr

1994, Levin and Hay 1996). This was demonstrated with experiments conducted in the Gulf of Maine (Levin 1994). Recently, pollock were seen for the first time in twenty years at sites formerly devoid of erect macroalgae (Steneck personal observation). Numerous invertebrate species also recruit to kelp habitats (Duggins et al. 1990). This suggests that a change in abundance at a lower trophic level, such as reduced herbivory causing an increase in kelp abundance, may control the recruitment potential and resilience of top predators such as groundfish.

Although there are economic advantages to population increases in lobsters and urchins, overall, the number of economically viable harvesting options have declined with the loss of formerly significant components of coastal food webs (Figures 17, 18). The loss of higher tropic levels resulted in increased fishing pressures on abundant species at lower levels. As finfish stocks declined, more effort focused on lobstering. The resulting pressure has risen to levels that some fear cannot be sustained. Recently a variety of intertidal and subtidal seaweeds have been harvested for food and fertilizer. Since the mid 1980s, an industry for small herbivorous periwinkle snails has developed (Chenoweth and McGowan 1994) and even more recently one has developed for predatory snails. There is growing concern that sea urchins, snails and sea weeds may be incapable of sustaining the escalating harvesting pressures on them because ultimately sustainability relies on the stability of harvested populations. When biodiversity is high, one species fished down can be compensated by another in that trophic level. What we face now is different. Entire trophic levels are being functionally eliminated - entire marine communities are being altered. Whereas prehistoric indigenous Americans may have had thousands of years of sustainable harvests, our current concerns of sustainability are on the scale of decades. The evidence is strong that biological populations throughout the Gulf of Maine have changed profoundly as a result of resource exploitation. The evidence is equally strong that similar changes have occurred and are occurring elsewhere (Duran and Castilla 1989 for Chile, Smith et al. 1991 for New Zealand, McClanahan and Muthiga 1988 for Kenya, Hughes 1994 for Jamaica, Underwood 1991 for Australia, Grigg 1994 for Hawaii, Pfister and Bradbury 1996 for Washington state, Aronson 1990 for the world). At this point it is important that we recognize these changes and try to understand their ecological consequences because without such knowledge, management of virtually any component of ecosystem will be impossible.

Acknowledgments

I thank Gordon Wallace and Larry Mayer for inviting me to write this paper. Many of these ideas evolved from discussions with Jim Acheson, Peter Auster, Ted Ames, Phil Conkling, Rich Langton, Wendy Malpass, Doug McNaught, Alvaro Palma, Bob Vadas, Rick Wahle, Steph Watson, Carl Wilson, Jim Wilson, Steff Zimsen and many others to whom I apologize for not naming individually. I also thank Bob Vadas, Jon Witman and Ken Sebens for the many years of stimulating collaborative research on Ammen Rock Pinnacle as we all explored the wonders of a system still dominated by large predatory fish. I received comments on this manuscript from Eugenia Braasch, Larry Mayer, Judith Pederson, Steph Watson, Jim Wilson and Steff Zimsen. However, all errors of interpretation and emphasis are attributable to me. Primary funding for research described here was from NOAA's National Undersea Research Program's National Research Center at the Univ. of Connecticut at Avery Point (Grant No. NA46RU0146 and UCAZP 94-121) and the University of Maine's Sea Grant program for funding my lobster research in coastal zones. Additional funds were provided by Maine's Department of Marine Resources via their Urchin and Lobster Advisory Councils. To all I am grateful.

References

Ames, T. unpublished.

Aronson, R. B. 1990. Onshore-offshore patterns of human fishing activity. *Palaios*. 5:88-93.

Aronson, R. B. 1994. Scale-independent biological processes in the marine environment. *Ocean and Mar. Biol. Ann. Rev.* 32:435-460.

Acheson, J. and R. S. Steneck. 1997. Examining the bust then boom in the Maine lobster industry: the perspectives of fishermen and biologists. *Trans. of the Amer. Fish. Soc.* In press.

Barnard, M. 1986. Sea, Salt and Sweat: a story of Nova Scotia and the vast Atlantic Fishery. Halifax, Nova Scotia: Four East Publications and The Nova Scotia Department of Fisheries.

Bigelow, H. B. and W. C. Schroeder. 1953. Fishes of the Gulf of Maine. *Fish Wildl. Serv. Fish. Bull.*, Vol. 53. 577 pp.

Bologna, P. and R. Steneck. 1993. Kelp beds as habitat for the American lobster, *Homarus americanus. Marine Ecology Progress Series.* 100:127-134.

Borque, B. J. 1996. *Diversity and complexity in prehistoric maritime societies: A Gulf of Maine perspective.* New York: Plenum Press.

Brown, B. E., J. A. Brennan, M. D. Grosslein, E. G. Heyerdahl, and R. C. Hennemuth. 1978. The effect of fishing on the marine finfish biomass in the northeast Atlantic from the Gulf of Maine to Cape Hatteras. *ICNAF Res. Bull.* 12:49-69.

Caldwell, B. 1981. *Islands of Maine: where America really began.* Portland, Maine: Guy Gannett Publishing Co.

Carlson, C. C. 1986. Maritime catchment areas: an analysis of prehistoric fishing strategies in the Boothbay region of Maine. Masters thesis, Quaternary Studies, University of Maine.

Carr, M. H. 1994. Effects of macroalgal dynamics on recruitment of a temperate reef fish. *Ecology*. 75:1320-1333.

Chenoweth, S. and J. McGowan. 1994. Periwinkles in Maine: Fishery and biology. Maine Department of Marine Resources. 14 pp.

Collins, J. W. and Rathbun, R. 1887. Fishing grounds of the eastern coast of North America. In *The fisheries and Fishing Industries of the U. S.* Section III. ed. G. B. Goode, Washington, D. C.: Printing Office.

Conkling, P. W. and T. Ames. 1996. Penobscot fisheries in the 20th Century. In *Penobscot: the forest, river and bay.* D. D. Platt, 46-65. Rockland, Maine:Island Institute.

Connell, J. H. and W. P. Sousa. 1983. On the evidence needed to judge ecological stability or persistence. *Am. Nat.* 121:789-824.

Duggins, D. O., J. E. Eckman, and A. T. Sewell. 1990. Ecology of understory kelp environments. II. Effects of kelps on recruitment of benthic invertebrates. *J. Exp. Mar. Biol. Ecol. 143:27-*45.

Duran, L. R. and J. C. Castilla. 1989. Variation and persistence of the middle rocky intertidal community of central Chile, with and without human harvesting. *Mar. Biol.* 103:555-562.

Frank, K. T. and W. C. Leggett. 1994. Fisheries ecology in the context of ecological and evolutionary theory. *Annu. Rev. Ecol. Syst.* 25:401-422.

Goode, G. B. 1884. Fishing Industries of the U. S. Section I. Washington, D. C. Printing Office.

Grigg, R. W. 1994. Effects of sewage discharge, fishing pressure and habitat complexity on coral ecosystems and reef fishes in Hawaii. *Mar. Ecol. Prog. Ser.* 103:25 -34.

Hacunda, J. S . 1981. Trophic relationships among demersal fishes in a coastal area of the Gulf of Maine. *Fish. Bull.* 79:775-788.

Hennemuth, R. C. and Rockwell, S. 1987. History of fisheries conservation and management. In *Georges Bank.* ed. R. H. Backus, 430-446. Cambridge, MA: MIT Press.

Hughes, T. P. 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. *Science*. 265 :1547-1551.

Levin, P. S. 1991. Effects of microhabitat on recruitment variation in a Gulf of Maine reef fish. *Mar. Ecol. Prog. Ser.* 75:183-189.

Levin, P. S. 1994. Small-scale recruitment variation in a temperate fish: the roles of macrophytes and food supply. *Environ. Biol. Fish.* 40:271-281.

Levin, P. S. and M. E. Hay. 1996. Responses of temperate reef fishes to alterations in algal structure and species composition. *Mar. Ecol. Prog. Ser.* 134:37-47.

Maine's Commissioner of Sea and Shore Fisheries Annual Report 1949. In *Penobscot fisheries in the 20th Century.* 1996. Conkling, P. W. and T. Ames. In *Penobscot: the forest, river and bay.* D. D. Platt, 46-65. Rockland, Maine:Island Institute.

Malpass, W. J. 1992. The ecology and resource use patterns of small, benthic, predatory fishes in rocky, nearshore habitats of the Gulf of Maine, U.S. A. Masters thesis, Department of Oceanography, University of Maine.

Martin, K. R. and N. R. Lipfert. 1985. *Lobstering and the Maine coast.* Maine Maritime Museum, Bath, Maine.

Mayo, R. K., M. J. Fogarty, and F. M. Serchuk. 1992. Aggregate fish biomass and yield on Georges Bank, 1960-87. *J. Northw. Atl. Fish. Sci.* 14:59-78.

McClanahan, T. R., N. A. Muthiga. 1988. Changes in Kenyan coral reef community structure and function due to exploitation. *Hydrobiologia*. 166:269-276.

Menge, B. A. and J. P. Sutherland. 1987. Community regulation: variations in disturbance competition, and predation in relation to environmental stress and recruitment. *Am. Nat.* 130:730-757.

Myers, R. A., J. A. Hutchings, and N. J. Barrowman. 1997. Why do fish stocks collapse? the example of cod in Atlantic Canada. *Ecol. Applic.* 7:91-106.

Ojeda, F. P. and J. H. Dearborn. 1989. Diversity, abundance, and spatial distribution of fishes and crustaceans in the rocky subtidal zone of the Gulf of Maine. *Fish. Bull.* 88:403-410.

Paine, R. T. 1969. A note on trophic complexity and community stability. Amer. Nat. 103:91-93.

Paine, R. T. 1980. Food webs: linkage, interaction strength and community infrastructure. *J. Anim. Ecol.* 49:667-685.

Pfister, C. A. and A. Bradbury. 1996. Harvesting red sea urchins: recent effects and future predictions. *Ecol. Applic.* 6:532-551.

Platt, D. D. 1996. *Penobscot: the forest, river and bay.* Rockland, Maine: Island Institute.

Rathbun, 1887. The lobster fishery. In *The Fisheries and Fishery Industry of the United States. Section V: History and Methods of the Fisheries.* G. R. Goode, Washington D. C.: U. S. Gov. Print. Office.

Rich, W. H. 1929. *Fishing grounds of the Gulf of Maine.* Bureau of Fisheries Doc. 1959:51-117.

Rosier, J. 1605. True relations of Capt. George Weymouth's Voyage. London: George Bishop.

Scott, W. B., and M. G. Scott. 1988. Atlantic fishes of Canada. Can. Bull. Fish.Aquat. Sci. 219:731 pp.

Sherman, K. 1991. The large marine ecosystem concept: research and management strategy for living marine resources. *Ecol. Applic.* 1:349-360.

Simenstad, C. A., J. A. Estes, K. W. Kenyon. 1978. Aleuts, sea otters, and alternate stable-state communities. *Science.* 200:403-410.

Sinclair, M. and F. Page. 1995. Cod fishery collapses and North Atlantic GLOBEC. *U.S. GLOBEC News.* 8:1-20.

Smith, J. 1616. *The description of New England.* London:H. Lownes.

Smith, P. J., R. I. C. C. Francis, and M. McVeagh. 1991. Loss of genetic diversity due to fishing pressure. *Fisheries Research* 10:309-316.

Steneck, R. S. 1982. A limpet-coralline algal association: adaptations and defenses between a selective herbivore and its prey. *Ecology* 63:507-522

Steneck, R. S. 1995. The Gulf of Maine: A case study of overexploitation. In *Fundamentals of conservation biology.* Hunter, M. L. Jr. 209-212. Blackwell Science.

Steneck, R. S. 1986. The ecology of coralline algal crusts: convergent patterns and adaptive strategies. *Ann. Rev. Ecol. Syst.* 7:273 -303.

Steneck, R. S. 1997. Are we overfishing the American lobster? Some biological perspectives. In *Decline of fisheries resources in New England: evaluating the impact of overfishing, contamination and habitat degradation.* eds. R. Buchsbaum, Robinson and Pederson. Mass. Bay's Program. In press.

Steneck, R. S. 1994. Is herbivore loss more damaging to reefs than hurricanes? Case studies from two Caribbean reef systems (1978 - 1988). In *Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History.* 220-226. 1993. Miami, Florida: Univ. of Miami. 420 pp.

Steneck, R. S. and M. N. Dethier. 1994. The structure of algal-dominated communities: a functional group approach. *Oikos* 69:476-498.

Steneck, R. S., D. McNaught and S. Zimsen. 1995. Spatial and temporal patterns in sea urchin populations, herbivory and algal community structure in the Gulf of Maine. 1994 Workshop on the Management and Biology of the Green Sea Urchin (*Strongylocentrotus droebachiensis*). 34-73. Mass. Dept. of Natural Resources.

Underwood, A. J. 1991. Ecological research and the management of human exploitation on the rocky coast of New South Wales. Occasional Paper #4, Australian Committee for IUCN, Proceedings of the 4th Fenner. 122-128.

Vadas, R. L. and R. S. Steneck. 1988. Zonation of deep water benthic algae in the Gulf of Maine. *J. Phycol.* 24:338-346.

Vadas, R. L.and R. S. Steneck. 1995. Overfishing and inferences in kelp-sea urchin interactions. pages 509 - 524. In *Ecology of Fjords and Coastal Waters.* eds. H. R. Skjoldal, C. Hopkins, K. E. Erikstad, and H. P. Leinaas. Elsevier Science B. V.

Wahle, R. A. and R. S. Steneck. 1992. Habitat restrictions in early benthic life: experiments on habitat selection and in situ predation with the American lobster. *J. of Experimental Marine Biology and Ecology.* 157:91-114.

Watson, S. M. 1996. Overfishing from a multiple scale perspective: implication for the efficient organization of fisheries management institutions. Masters thesis, Ecology and Environmental Sciences, University of Maine.

Witman, J. D. and K. P. Sebens. 1992. Regional variation in fish predation intensity: a historical perspective in the Gulf of Maine. *Oecologia.* 909:305-315.

Nutrients and Human-Induced Change in the Gulf of Maine — "One, if by land, and two, if by sea"

John R. Kelly

Abstract

Recognizing that nutrients play a strong role in regulating water quality and the trophic status of aquatic ecosystems, nutrient inputs to coastal waters have become a national concern because of burgeoning human populations and expanding use of the coastal zone. Concerns generally focus on issues like dissolved oxygen depletion, stimulation of nuisance/noxious species, and food web change, with the critical issues varying regionally and locally. For a large area such as the Gulf of Maine, many aspects of scale (space and time) are important in determining these critical issues. Biotic and abiotic factors regulating nutrient inputs, concentrations, species, and food webs vary as a function of scale, and this creates further uncertainty in whether the undesired symptoms of over-enrichment will be expressed or detectable. Rather than try to examine all spatial scales of interest in the Gulf of Maine, the focus of this paper is inshore, near-coastal waters. Here, the role of nutrients is especially complicated by physical processes including tidal advection and mixing — factors which make the application of existing limnological models for water quality management a bit tenuous. The central theme of this paper is how physically-mediated interactions between estuaries and their adjacent shelf ecosystems complicate sensitivity and predictability of ecological response to changes in nutrient inputs discharged from land. Examples are drawn from an extensive case study of (highly-loaded) Boston Harbor and adjacent shelf waters in western Massachusetts Bay. Contrasts are drawn between Boston Harbor-Massachusetts Bay and other less enriched coastal systems, including a set of nineteen estuaries and embayments along the coast of Maine. A simple conclusion: for some coastal ecosystems in the Gulf of Maine we must know inputs from the sea to know the effects of changes in coastal watersheds and their loading to estuaries.

Introduction

The potential undesired effects of increasing nutrient inputs to coastal waters are familiar, if not well understood and predictable. Coarsely, the effects of concern may be classified as (1) water quality issues (e.g., water clarity, formation of surface or fouling scums from excessive growth, levels of dissolved oxygen), not fully independent from (2) biological/ecological character issues (e.g., food web change, promotion of less desired species) or (3) human health issues (e.g., stimulation of PSP or other toxins that accumulate in tissues, affect fisheries and seafood product edibility). There are instances where these concerns have been linked, with varying degrees of confidence, to variations in nutrient concentrations and inputs (some human-induced). However, coastal systems are dynamic, diverse, and are influenced by many biological, chemical, and physical process that operate across a range of spatial and temporal scales. Accordingly, while we understand the broad issues related to nutrient enrichment, prediction of specific responses to given changes in nutrient flows in unique situations is still not well advanced. As examples for the interested reader, Nixon et al. (1984, 1986) and Nixon (1995) broadly have reviewed evidence on potential biological effects of coastal eutrophication, while Kelly (1991, 1993) and Kelly and Doering (1995, 1996) have reviewed progress on understanding a variety of possible enrichment effects for the specific case of Boston Harbor/Massachusetts Bay, within the Gulf of Maine. Compared to freshwater systems, there is still a strong need to characterize and classify a number of critical dynamics in coastal systems that can affect the expression of biological and environmental effects of nutrient enrichment.

There are many scales of interest and ecological significance in a region as large as the Gulf of Maine. Although information is spotty, the Gulf of Maine has both localized and wide-scale contamination issues similar to the rest of the United States east coast even though much of the region is not highly populated/developed (Larsen 1992, McDowell, these proceedings). With respect to nutrients, Christensen et al. (1996) and Townsend (these proceedings) have examined and summarized some water quality aspects at the basin-wide scale and developed an understanding of the nitrogen budget, especially with respect to sinks for nitrogen inputs. This paper has a different scale of perspective than the whole Gulf. It describes aspects of nutrient enrichment at more localized scales, by emphasizing estuaries, embayments, and nearshore shelfwater systems — areas which abound in number and diversity in the Gulf of Maine and which are most immediately adjacent to the activities of a burgeoning human population. Examples from studies of Boston Harbor, Massachusetts Bay, and a number of Maine estuaries and embayments are used as foundation for underlying themes. A main theme centers on identification and elaboration of specific roles for tidal and other physical factors in regulating the expression of nutrient enrichment in coastal waters. A subtheme is the importance of environmental variability in shelfwater systems, for the role of oceanic inputs to inshore coastal systems is important in many local areas, particularly within the Gulf of Maine, and has been under-appreciated in terms of research and environmental management.

Loading and flushing

In recent decades there have been efforts to characterize variability in nutrient inputs to coastal ecosystems. While such estimates always have some uncertainty, there are many systems for which nutrient loading from land discharges (surface runoff, riverine discharges, effluent point sources, groundwater) and from atmospheric deposition have been quantified. In the case of nitrogen (N), a nutrient of prime interest in coastal waters, watershed-derived loading has been compared to *in situ* water column concentrations; some interesting patterns have been revealed (Figure 1). In comparing data gathered for Boston Harbor to other coastal ecosystems, it was striking that the Harbor had low *in situ* concentrations for its very high nitrogen input per area or volume (Figure 1, top). However, accounting for the fact that Boston Harbor is fairly rapidly flushed by tides (Signell and Butman 1992), it's N concentrations appear quite comparable to the trend observable for other systems (Figure 1, bottom). Studies to enable a nitrogen input-output budget have confirmed that denitrification in the sediments remove a fraction (~10%) of the input N (Nowicki et al. 1997), but most is exported to western Massachusetts Bay by active tidal exchange (Kelly 1997). The Boston Harbor case reveals some of the significance of flushing to estuarine and embayment water quality.

Various enrichment concerns stem from excessive growth of plant biomass (often measured as chlorophyll) and there is considerable evidence that chlorophyll and N concentrations are strongly related. Therefore, knowledge and prediction of *in situ* N concentrations are one simple, yet key, indicator of enrichment and potential vulnerability to undesired effects of eutrophication. Figure 1(bottom) suggests that *in situ* concentrations directly reflect loading after normalizing for how long water resides in the system. This general result is not especially surprising. In theory, the residence-time normalized loading (as expressed in Figure 1, bottom) directly predicts equilibrium concentrations (note that units of the X-axis convert to μM, the same as used for concentration) in the case where there are no strong "internal sinks" to remove nitrogen from the resident water (such as denitrification, with conversion of inorganic N as nutrient salts to N_2 gas, and its loss to the atmosphere). Barring strong denitrification (or other strong sink), the likelihood of which should increase as water residence times increase (Nixon et al., 1996), one should expect the overall trend in Figure 1. A 1:1 relationship was demonstrated statistically in enrichment studies using experimental marine mesocosms, where flushing was constant across a gradient of nitrogen input (Kelly et al., 1985; cf., Nixon et al. 1986; Nixon 1992). There may be coastal ecosystems where the implied linear relationship is not strongly followed. For example, there may be situations where nutrient inputs are

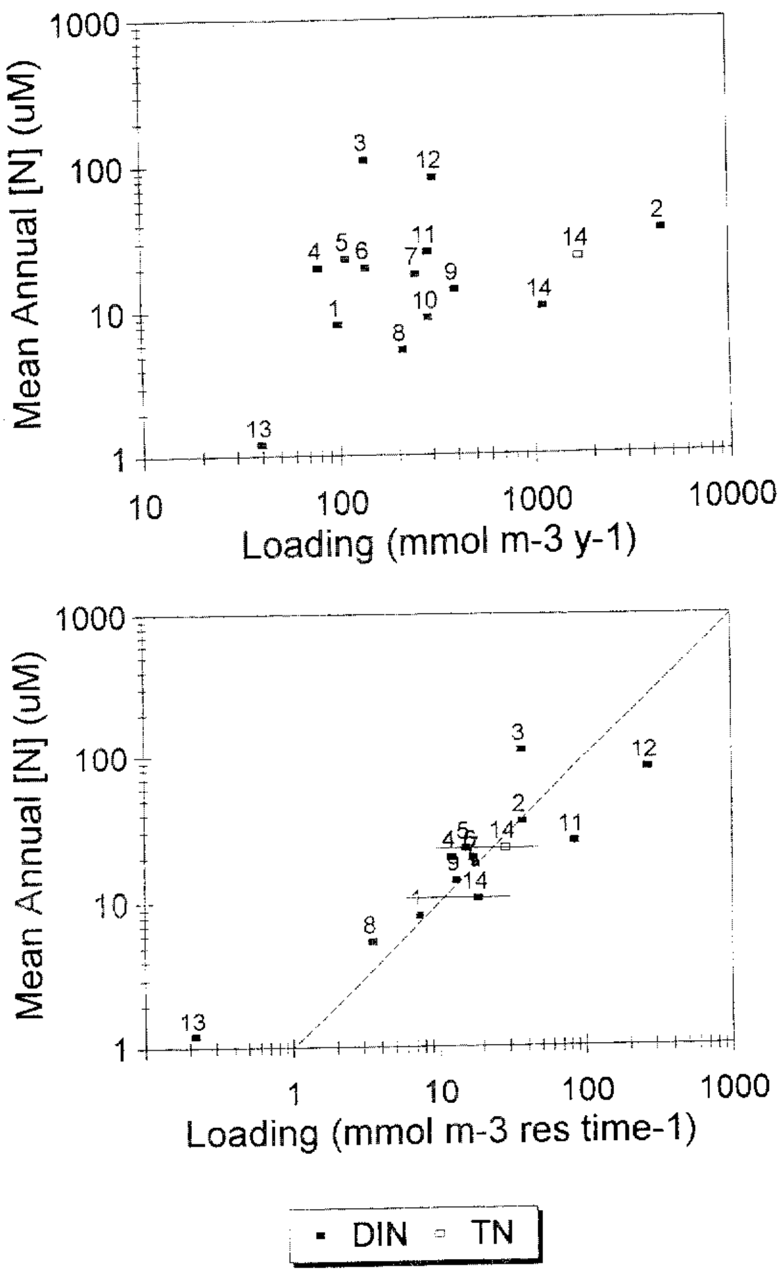


Figure 1. Mean annual N concentrations as a function of annual N inputs. Top panel: volumetric loading. Bottom panel: volumetric loading is corrected by an estimate of water residence time in each system. Except Boston Harbor (system 14), data are from Nixon (1983) and display DIN (= dissolved inorganic N). Boston Harbor data are summarized by Kelly (1997) for both DIN and TN (= total N). Dashed line shows a 1:1 relationship between loading and concentrations. (Modified from Kelly 1997)

extremely low and nutrients are retained in forms that are flushed at a different characteristic time-scale than water alone, or where extensive macrophytes or seagrasses affect *in situ* total N concentrations. More situations should be examined, for anomalies (like Boston Harbor) provide insight and often lead to much improved understanding.

Figure 1 and the Boston Harbor case study strongly emphasize the importance of physical flushing (be it driven by freshwater flows or tidal mixing/exchange) as a factor shaping vulnerability to eutrophication, but it is recognized that the relationship in Figure 1 is not satisfyingly predictive. Some scatter in the overall trend undoubtedly arises from uncertainties and natural interannual variability in values for input, average concentrations, and flushing. The pattern should be considered in light of recent trends in coastal monitoring and management. It is a very substantial effort to obtain reliable estimates of inputs and to characterize flushing of coastal systems (the two elements of the X-axis), both of which vary in time. In this context, highly precise estimates of inputs from watersheds (a strong emphasis in current research/management efforts) may not be particularly useful if flushing, which is very difficult to characterize precisely, is only crudely estimated. In contrast, characterizing annual mean concentrations is not particularly difficult and, based on evidence presented in Figure 1, one implicitly incorporates the effects of flushing in the measurements. In principle, measurements of the actual concentrations thus bring one closer to understanding of vulnerability to enrichment in a given system, especially if they do roughly equate to flushing-normalized loading.

Knowing nutrient inputs is important and has advanced understanding, but the point is that we could probably now learn more about biological effects of nutrients by measuring system attributes (including water quality [like N concentrations] and biological character than by getting ever-more precise estimates of loading from watershed-derived nutrient inputs, especially when there is poor characterization of flushing and its variability. This simple point may be self-evident but it is highlighted for two principle reasons. First, there is inherent, added value in improved understanding of the system itself. The scatter in Figure 1 is itself illustration of limits of general predictability that a diversity of coastal systems will have in response to loading, even when the simplest, most direct connection is explored — i.e., input flux and resultant concentration. Predicting ecological (vs. concentration) responses in different physical, geological, morphometric, and biological settings involve far more subtle and indirect linkages, greater variability, and thus inherently less general predictability. Continued *in situ* research and monitoring studies of different settings are absolutely warranted, for the ecological "response" to enrichment for one type will not be fully applicable to all. Second, watershed loadings are only a portion of the total loading to open coastal systems. To characterize only a part of the loading "stimulus" for biological effects is to foster misunderstanding of the ability to regulate nutrient "effects". This lesson was learned as it became evident that atmospheric deposition to some systems (particularly larger estuaries, like Chesapeake Bay) were substantial. As this paper continues, evidence is given for many cases in the Gulf of Maine where oceanic inputs are very significant and, like atmospheric deposition, cannot be ignored. It is recognized that the role of oceanic loading to coastal systems (not included in Figure 1) deserves stronger characterization (e.g., Nixon et al. 1995).

Boston Harbor–Massachusetts Bay region

Boston Harbor is an example where high watershed nutrient loads are the dominant input, but where tidal flushing moderates *in situ* conditions and promotes high nutrient export that, in effect, extends the influence of the watershed to the shelfwaters of Massachusetts Bay (Kelly 1997). It has provided an interesting environmental setting to examine Harbor-Bay interactions that bear upon nutrient enrichment issues. There is a consistently observable gradient of decreasing N concentrations radiating into the surface waters of western Massachusetts Bay (Figure 2). Studies using high-resolution towed instrumentation were conducted throughout 1994 to gain a more detailed understanding of conditions across this gradient (Kelly et al. 1995). The area of particular interest extended from within Boston Harbor, past the present Deer Island Massachusetts Water Resources Authority (MWRA) outfalls, to about 15 km into Massachusetts Bay (~32 m water depth), where a future MWRA outfall will deliver effluent through risers from the seabed. Water quality and dynamics should change sharply in this area when the effluent is diverted offshore.

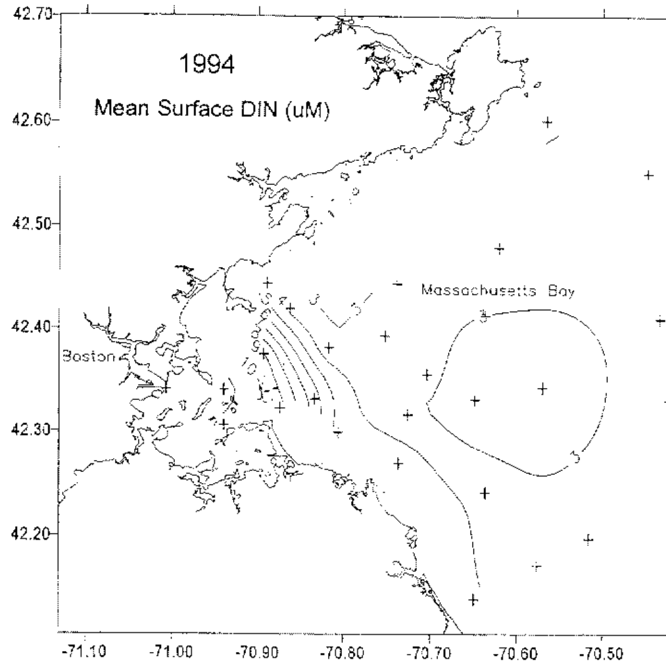


Figure 2. DIN concentration gradient from Boston Harbor into Massachusetts Bay (From Kelly 1997)

Figure 3 (next page) illustrates seasonality in the nature of bio-physical interaction between the Harbor and the Bay and is derived from repeated observations made along a ~20-km long transect. Kelly et al. (1995) described three fundamental cases associated with different seasons, as next synopsized.

Case 1 (Figure 3, top). In the wintertime conditions, there is a period when the winter-spring bloom

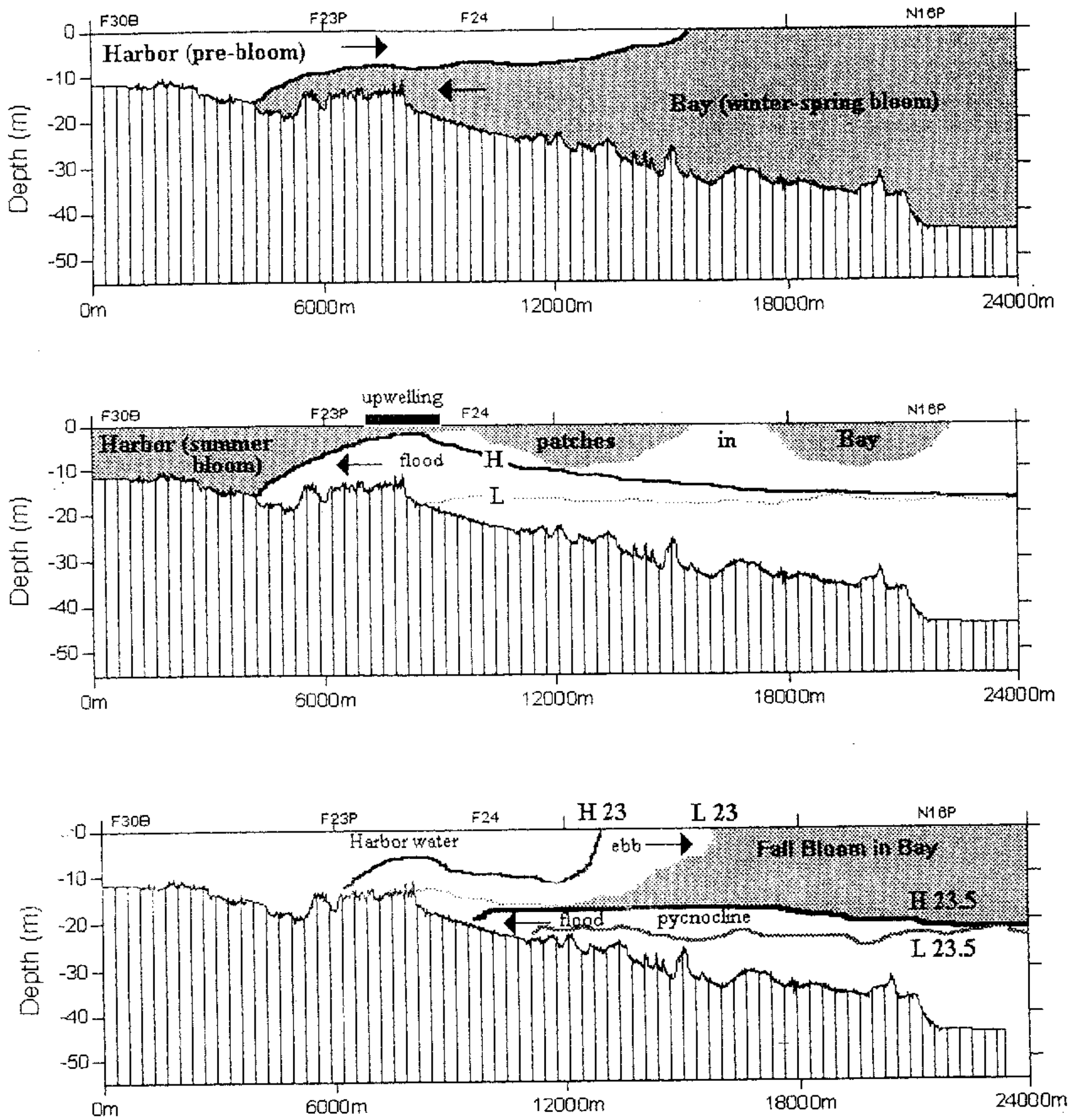


Figure 3. Seasonal paradigms for physical and ecological interaction between Boston Harbor and Massachusetts Bay (Modified from Kelly et al. 1995). Labels across the top of each panel are station codes. 'H' and 'L' show pycnocline at high and low tides; bottom panel shows 2 σ_T surfaces (σ_T=23 and 23.5) at high and low tide.

has been initiated in the Bay but not yet in the Harbor. During tidal exchange, there must be an import of chlorophyll to the Harbor. It appears that chlorophyll input may occur in bottom water inflow, since there is general freshwater outflow suggested at the surface. Using salinity as a conservative tracer, Kelly (1997) suggested that there is substantial Harbor export of dissolved nutrient forms in surface water at this time. The Case 1 hypothesis is that Harbor-Bay coupling involves export of dissolved nutrients from the Harbor and import of some organic matter produced within the Bay, which in part is supported by the dissolved nutrient export.

Case 2 (Figure 3, middle). The nature of the coupling is qualitatively reversed in the summer, when chlorophyll concentrations in the Harbor generally exceed those in the Bay. The situation implies export of chlorophyll (and thus some organic matter produced within the Harbor) to the Bay during tidal exchange. The general chlorophyll gradients depicted from inshore to offshore during summer, although often being a patchy distribution, are broadly characteristic of the region and indicative of export of chlorophyll to the Bay in near-surface waters. Dissolved nutrients, although slightly enriched within the Harbor (primarily NH_4^+), are generally low throughout the Bay during summer. Kelly (1993, 1997) provided evidence that the primary surface-water export during summer stratification involves organic and particulate nutrient forms, including plankton biomass (indicated by chlorophyll). The Case 2 hypothesis suggests there is chlorophyll (and organic matter) export in surface water, but at the same time some dissolved import from the Bay in water from within the pycnocline. Whether dissolved nutrients from depth in the Bay offer a feedback conduit to Harbor-Bay cycles through tidal exchange processes may depend on the precise meterological and tidal phase conditions. For example, Signell and Butman (1992) suggested the morphometry of the Harbor entrances may promote a phenomenon of "tidal pumping" (Stommel and Farmer, 1952; see also Geyer and Signell, 1992) and one would expect greater dispelling of export into the Bay on spring tides. The previous studies did not have the benefit of detailed understanding of the vertical structure of the water column offered by our observations. Here we additionally suggest that, while "pumping" seems a reasonable concept and fairly apt descriptor, it is also possible that bathymetric-induced upwelling, also a function of tidal phase and current strength, may act to interrupt outflow such that tidal cycles produce discrete or semi-discrete parcels which then advect with Bay circulation and mixing. These parcels during summer are characteristically laden with higher turbidity and chlorophyll (compared to the receiving Bay water), so the term "tidal puffing" seems appropriately descriptive.

Case 3 (Figure 3, bottom). In fall (late September) chlorophyll concentrations again are characteristically higher in the Bay than in the Harbor. Thus, this case has some similarity to Case 1 conditions. However, it differs from the first case because chlorophyll influx to the Harbor in late fall may occur only when waters within or above the pycnocline are exchanged during tidal processes; deep stratification precludes bottom-water exchanges. Probably the more ecologically significant feature of the interaction at this time relates to surface output. Nutrient concentrations are typically higher in the Harbor in early fall (e.g., Kelly and Turner, 1995 a, b). In this case, a hypothesis is that nutrient export can help feed the fall bloom in the Bay at the seaward edge of the tidal front.

Hypotheses notwithstanding, a firm conclusion is that there is considerable variability in the fundamental nature of communication between the Harbor and the Bay. While tidal mixing is significant for the Harbor, the quality of the Harbor's export and its potential influence on the Bay varies with season. If the Harbor were not so highly loaded, seasonal variability in the tidal input from the Bay would be more ecologically significant; but a clear lesson learned is that a number of physical factors influence the present interaction between the Harbor and the Bay (Table 1). Recent efforts on Harbor and Bay physical circulation and modeling (e.g., Signell and Butman, 1992; Signell et al., 1996; Geyer et al., 1992; Adams et al., 1992) have strongly emphasized the impact of variability in all the features of Table 1 except the depth of the thermocline.

Tidal mixing in the Harbor generally limits water column stratification, but seasonal stratification of the Massachusetts Bay water column (Figure 3), coupled with it's strong nutrient load from the Harbor, raises a principal concern with enrichment — dissolved oxygen (DO) concentrations and the problem of anoxia/hypoxia. The western Bay has high primary productivity (~300-600 gC m^{-2} $yr.^{-1}$) commensurate with high nutrient export and loading (Kelly and Doering 1996). The potential of high rates of metabolism to depress dissolved oxygen (DO) during stratification is thus of interest. For each year of the period 1992-1994, a progressive decline in DO concentration in bottom water through summer into fall was characteristic of the thermally stratified western Massachusetts Bay waters (e.g. Figure 4). Modeling, in part based on empirical observations of water column and sediment respiration, projected that total respiratory demand on DO was >2 times the observed decline (Kelly and Doering 1995). Additional factors besides metabolism must help regu-

Table 1.
Physical Features Influencing Variability in the Nature of Harbor-Bay Interaction. (From Kelly et al. 1995)

Feature	Mechanism of Influence	Suggested Effect on Interaction
Depth of thermocline/pycnocline in Bay	Controls the depth and layer of Bay water that flood into the Harbor	Communication between surface and bottom layers in Harbor and Bay
Tidal height (e.g., spring vs. neap tide volumes)	Interacts with depth of thermocline to regulate quality of flooding water	Communication between surface and bottom layers in Harbor and Bay; degree of tidal pumping at inlets
Freshwater flow volume	Alters density differences between Harbor and Bay, as well as vertical layering	Strength of export flow and degree of two-layer estuarine circulation
Meterological conditions (e.g., wind speed, direction, variability)	Modifies surface flow	Modulates two-layer flow; affects upwelling vs. downwelling phenomenon

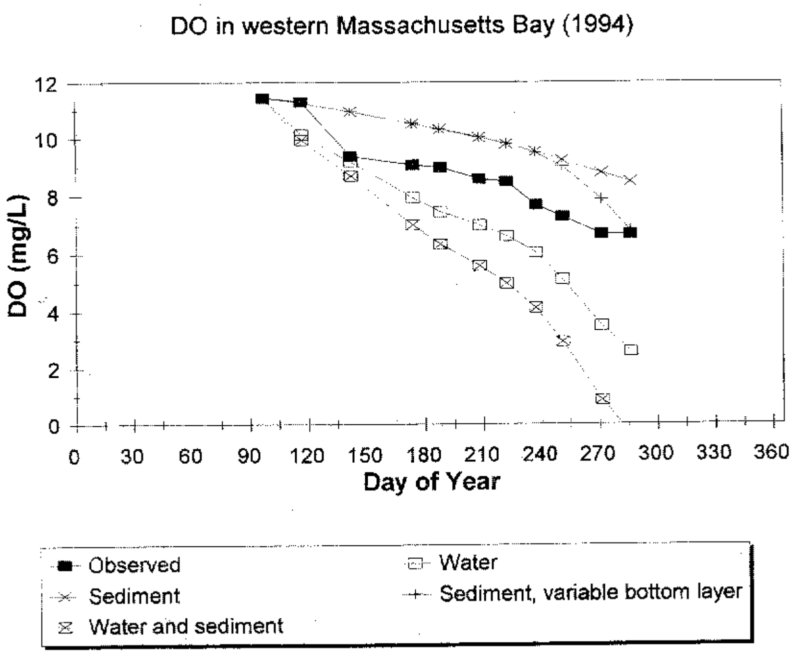


Figure 4. Comparison of Dissolved Oxygen observations to model-projections. (Modified from Kelly and Doering 1995)

late DO concentrations in these bottom waters, and one logically assumes that these factors are physical. Assuming an eddy-diffusion coefficient (k) of 0.05 to 0.1 cm^2 sec^{-1} during strong summer stratification (Geyer, pers. comm.), observed DO summertime gradients between the surface and bottom layer (1-2.5 mg L^{-1}, higher at the surface), and a boundary thickness of 5 m, one calculates a flux of DO into the bottom layer of 0.01 to 0.02 mg O_2 L^{-1} d^{-1}. Such a flux is of the correct order of magnitude to balance or at least moderate subpycnocline respiratory demands, if the rate were appropriate for the entire stratification period. This is a simple first-order calculation, but suggests that downward vertical transport could influence the decline of DO in bottom layers during stratification. Kelly and Doering (in prep) have conducted more comprehensive modeling of DO in near-bottom water in Massachusetts Bay; results suggest that DO concentrations are also very sensitive to physical features including near-bottom temperature and seasonal variability in the vertical density structure of the water column.

One model projection of Figure 4 uses a fixed depth of the pycnocline, whereas the actual trend indicated that the pycnocline deepened over the period, reducing the thickness of the subpycnocline bottom layer. For comparison, progressive deepening of the thermocline is also modeled in Figure 4 (labeled "variable bottom layer"). Deepening of the pycnocline and "compression" of the bottom layer, in principle, intensifies the influence of benthic metabolism upon subpycnocline waters, without changing the contribution of water column demand. Such an effect is apparent when comparing the two curves for partitioned respiratory demands of sediment metabolism in Figure 4.

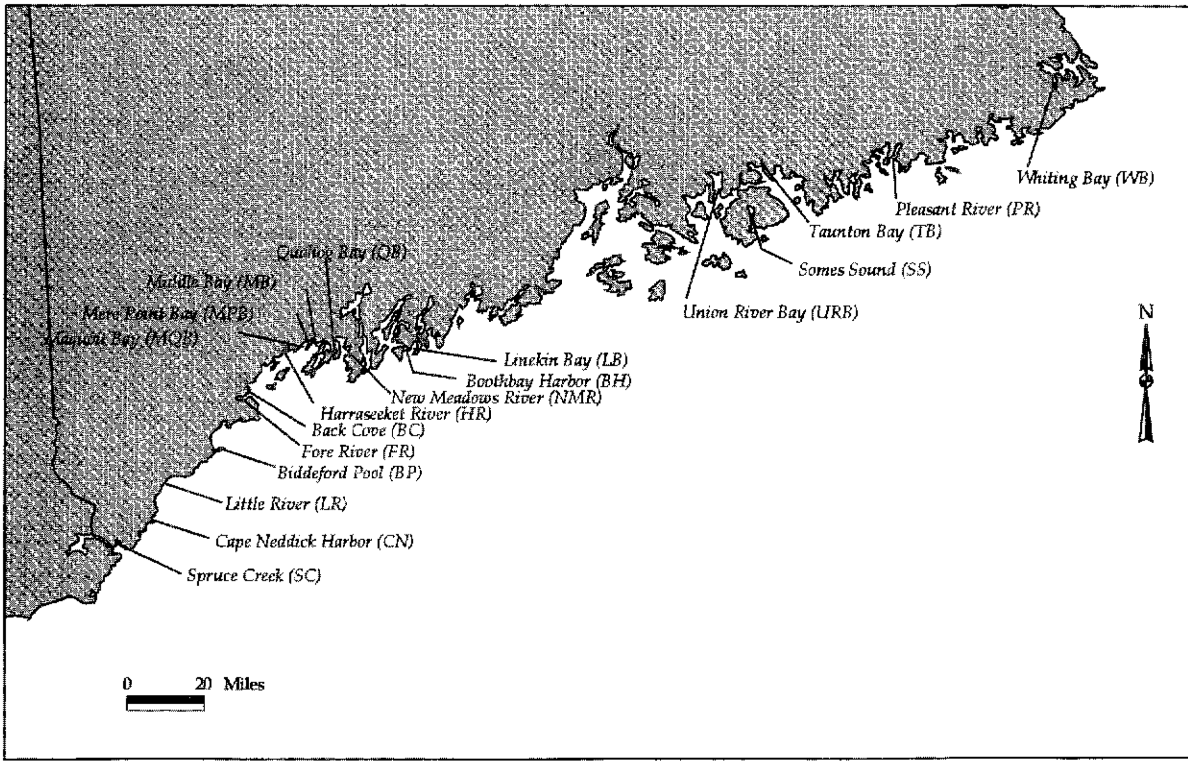


Figure 5. Maine estuaries and embayments studied in 1995

There are a number of intriguing aspects of Figure 4. For the themes of this paper, results reinforce the significance of stratification in promoting a seasonal DO decline. Observations and modeling suggest how variability in the depth, as well as intensity, of stratification may contribute to observed interannual variability in bottom-water DO concentrations (Kelly and Doering 1995); moreover, the balance of pelagic and benthic respiratory demands on water column DO in principle are sensitive to pycnocline variability. As classically appreciated, stratification promotes seasonal DO declines by separating surface autotrophic (production) and bottom heterotrophic (consumption) layers. Interestingly, however, the analysis here suggests that the separation may not be complete where it creates a strong concentration gradient across the pycnocline, promotes diffusion of oxygen from the surface mixed layer to bottom sub-pycnocline layer, and thereby moderates the effect of the physical structure.

Western Massachusetts Bay has relatively high nutrient loading, high *in situ* metabolism, and is strongly seasonally stratified. Were it not for its relative depth (~32 m average for the ~100 km^2 region summarized in Figure 4), this would seem a good recipe for promoting lower DO (see also below). Spot measurements of values ~5 mg L^{-1} have been made, but the annual minima in bottom waters, reached just prior to fall overturn, has averaged above 6 mg L^{-1}. In contrast, DO of 2 mg L^{-1} is often used as a threshold fo hypoxia.

Vulnerability of Maine embayments, with a focus on Dissolved Oxygen

As a counterpoint to the Boston Harbor-Massachusetts Bay region, it is useful to compare some attributes (water quality, physical factors, and potential loading sources) of coastal systems that are far less enriched with nutrients from watershed sources. Survey studies conducted in 1995 by researchers from the Maine Department of Environmental Protection, Casco Bay NEP, and Wells National Estuarine Research Reserve included 19 different estuaries and embayments along the coast of Maine (Figure 5). Studies initially focused on DO, as a prime endpoint of concern with eutrophication, and as a potential indicator of the present vulnerability along this extensive stretch of the Gulf of Maine.

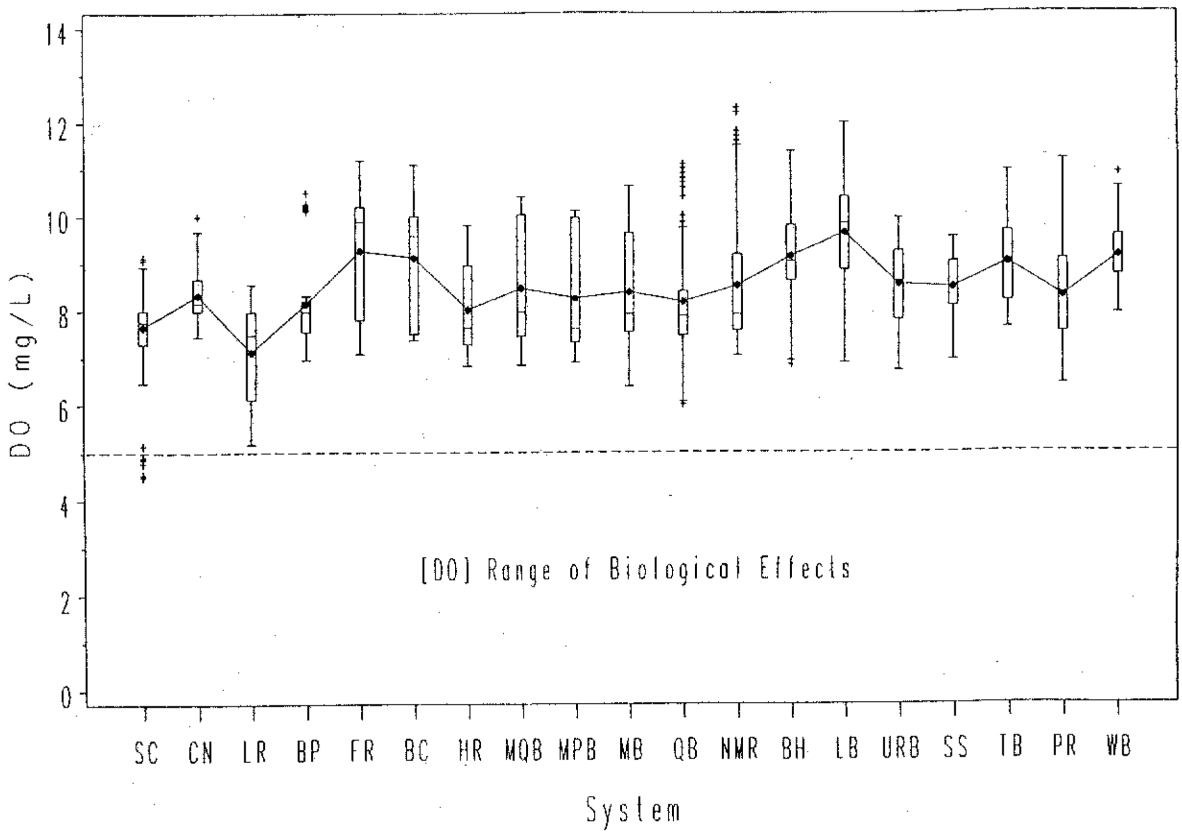


Figure 6. Box and whisker plots of all dissolved oxygen (mgL^{-1}) data in 1995. Data are presented by system geographically from south to north. Mean values are shown by the connected dots. Boxes showing interquartile ranges and extreme values are indicated by individual crosses. The dashed line at 5 mgL^{-1} indicates a Dissolved Oxygen level below which biological effects have been observed in other studies. (From Kelly and Libby 1996a).

Figure 6 summarizes measured DO concentrations in late summer and fall, when annual DO minima characteristically occur. The data indicate no general problems in the areas sampled; interestingly, DO concentrations for all data over time, space and depth only infrequently reached levels observed in the stratified bottom layer of western Massachusetts Bay (cf., Figures 4 and 6). The systems examined were generally shallow, mostly well mixed, and had estimated tidal flushing times ranging from <1 day to several days (comparable or faster than Boston Harbor) and included areas with developed watersheds (e.g., Fore River, South Portland), but mostly had low human populations and undeveloped watersheds. Overall the systems examined were not highly loaded from their watersheds (certainly not like Boston Harbor). They generally had low freshwater input, and had large tidal ranges and substantial flood-tide water volume input. However, DO concentrations did vary significantly among systems. Statistical analyses (Kelly and Libby 1996 a, b) showed that lower DO concentrations (as system averages or minima) were related to several features: (1) negatively, to freshwater input per unit area of the system, (2) positively, to the tidal range, and also (3) negatively, to the degree of the stratification of the water column. The lowest DO concentrations were characteristic of shallow system having a relatively high freshwater input and strong water column density stratification, whereas higher DO was more characteristic of systems with highest tidal range, low freshwater inputs, and which were well-mixed. Detection of an influence of stratification was not surprising (as considered above), but an intriguing result was the suggestion of opposing influences of tidal and freshwater inflow processes.

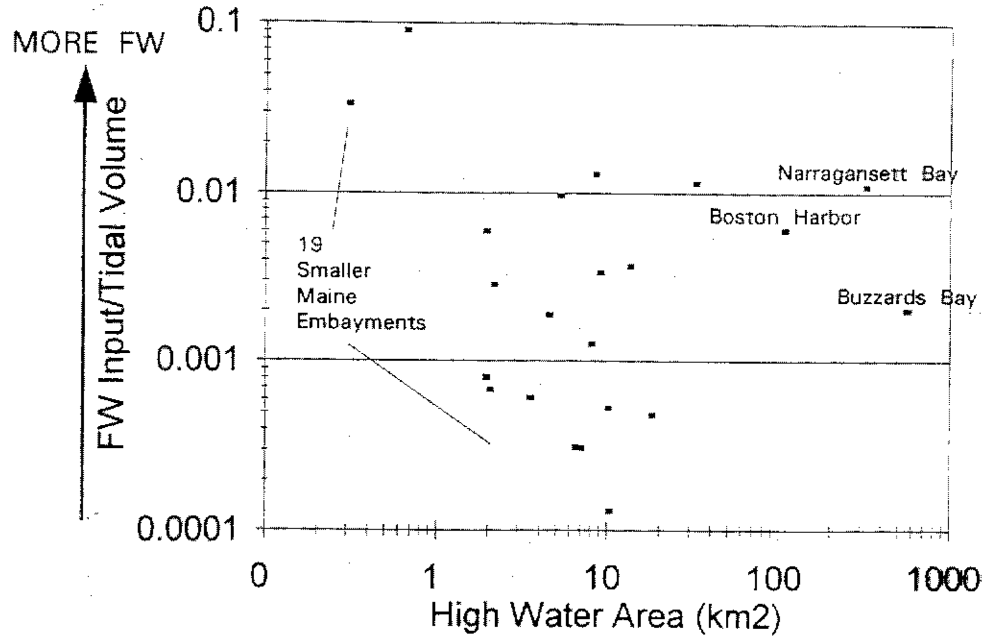


Figure 7. Ratio of freshwater volume input to tidal flood as related to area for a number of Gulf of Maine and New England costal systems. (Modified from Kelly and Libby 1996a)

Freshwater and oceanic inputs to coastal Gulf of Maine ecosystems

One element of the Maine DO study was a classification of physical and geomorphological attributes by system. The data allow an expression by which to illustrate the potential influence of tidal inflows relative to flow of water from the watershed, the opposing features statistically related to DO trends (above). The ratio of freshwater input volume to tidal input volume is shown in Figure 7 for the studied Maine systems, Boston Harbor, and a few other well studied New England coastal systems. These systems are generally high-salinity (>27 PSU) estuaries or embayments. Values of the ratio indicate that many systems, of different sizes, have freshwater inputs from land that are <1% of the tidal flood volume. Indeed a number have a ratio <0.1%! A simple perspective allows that, for a system with a ratio of 1/100, the effective concentration of nutrients associated with freshwater flow from the land must be 100 times the concentration in the tidal floodwaters if the land discharge were to deliver the greater mass of nutrients into the system. This situation can occur when effluent inputs are high and dominate freshwater inputs, because effluent concentrations for N can be >>10^3 μM, while the ocean input concentrations often will be ~10 μM.

Boston Harbor is the case in the region with very high land-derived nutrient inputs, primarily from the effluent presently discharged into the Harbor. The ratio of N concentrations in freshwater vs. oceanic inputs for much of the year is effectively high enough to dominate, even though the tidal prism volume is ~100 times the average freshwater input (Figure 7). When MWRA effluent is diverted offshore the freshwater input/tidal volume ratio may nearly halve because roughly half of the freshwater now going into the Harbor is effluent. Moreover, the effective concentrations in the future freshwater input will drop sharply; in that case, the concentrations and input from the ocean will have a more substantial role in creating the water quality in the Harbor (cf., Adams et al. 1992; Kelly, in prep).

Comparisons are possible with other areas. For example, a rough calculation for Narragansett Bay suggests a higher relative freshwater input than Boston Harbor (Figure 7). Even so, for Narragansett Bay (which receives considerable effluent input into the heavily populated upper estuary around Providence River), the most current budget analysis suggests the ocean may contribute significantly, perhaps 15-20% of the total nitrogen load (Nixon et al. 1995).

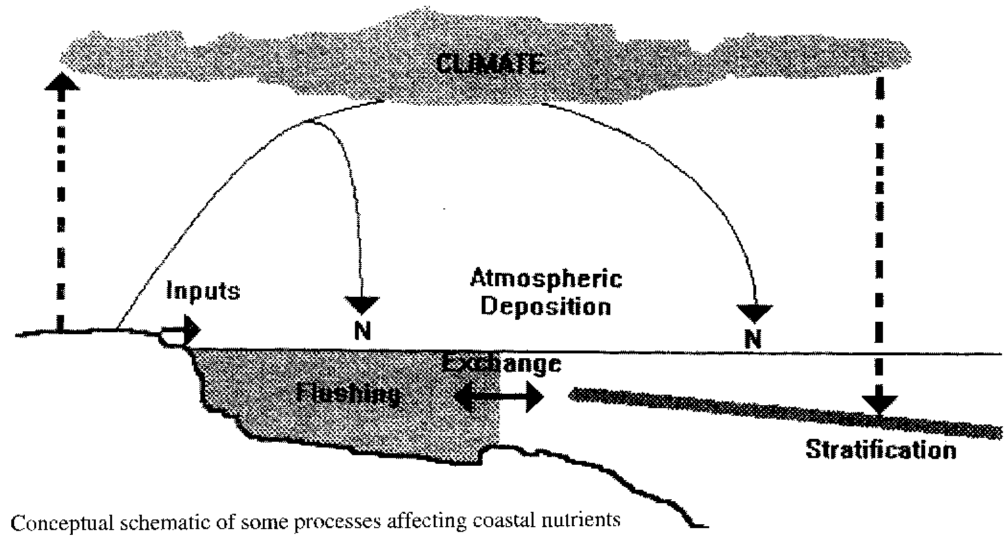


Figure 8. Conceptual schematic of some processes affecting coastal nutrients

In contrast, Garside et al. (1978) concluded decades ago that the major input of nitrogen into the Sheepscot estuary in Maine was from the ocean; land sources were relatively insignificant. Considering the low ratios shown for many systems in Figure 7, such a conclusion is likely to be applicable in many cases, even today. Somes Sound, a part of the Maine survey described above, also has been recently studied in the context of a nutrient budget. It has low freshwater input and a ratio slightly higher than 1/1000. Somes Sound does not have a highly developed watershed, so the concentrations of nutrients from land discharge are not very high, and certainly do not approach 10^3 times the adjacent shelfwater (~1-10 μM). An extensive study and associated modeling exercise has indicated indeed that the oceanic nutrient inputs strongly dominate the total input to the Sound (Doering and Roman 1994). Simple steady state modeling further suggested that a 20% increase in freshwater input of nutrients would have little effect on *in situ* nutrient concentrations, while a 20% increase in oceanic loading would increase concentrations nearly 20%.

Finally, a larger spatial scale has been examined in sensitivity runs of a water quality model developed for the entire Massachusetts and Cape Cod Bay region (Hydroqual 1995), including Boston Harbor. In simulations where 25% of the oceanic boundary nutrient flux (i.e., input to the Bays in water flow across a Cape Ann-Cape Cod model boundary) was eliminated, background concentrations of *in situ* water column nitrogen were noticeably reduced throughout most of the region.

Concluding synopsis and prospectus

These examples and calculations bring us to a conclusion heralded by the paper's subtitle — the well-known quotation from Longfellow's epic poem of Paul Revere's midnight ride to warn of the direction of the impending British assault upon Revolutionary forces. Both land and oceanic inputs can shape water quality and ecological conditions in coastal systems of the Gulf of Maine. While one signal light has been adequate to indicate the dominance of land-derived sources of nitrogen input to Boston Harbor for many years, two signal lights would be appropriate for many undeveloped areas having strong tidal input and mixing.

Human activities dramatically can affect land-derived discharges and lead to some over-enrichment problems. To the extent human-related activities also can alter atmospheric deposition to shelfwaters and indirectly increase oceanic inputs to inshore systems, or affect climate and induce variability in coastal stratification or circulation, these additional environmental perturbations may ameliorate or exacerbate enrichment problems in some coastal systems.

A conceptual schematic summarizes the features influencing the nutrient status of estuaries and nearshore shelf systems which emerge from examples in this paper (Figure 8). Studies have alerted us to the significance of flushing (including that which is tidally-mediated) in shallow coastal estuaries and embayments — water residence times will mediate the effect of nutrient inputs from human activities in watersheds. Humans also alter nutrient inputs to coastal systems by the pathway of atmospheric deposition, by direct deposition, but also perhaps indirectly by enhancing concentrations in shelfwater which enters inshore systems with tidal flooding. Given low ratios for freshwater/tidal input volumes, it is easy to project, as suggested directly by one detailed study (Doering and Roman 1994), that a small change in the shelfwater condition (such as through changes in atmospheric deposition or coastal circulation) could be much more influential than a similar or even much larger change in land-derived loading. Climate variability, human-influenced or not, can potentially affect flushing and tidal exchange dynamics through changes in timing or strength of stratification. The Boston Harbor-Massachusetts Bay case suggests that variability in stratification can play a critical role in estuary-shelf exchange and the expression of DO effects in shelfwater, as well as inshore systems that were typified by the Maine survey analyses. As a research issue, we must more fully characterize the critical roles of oceanic inputs (water and nutrients) and of other physical factors (flushing, stratification) if we are to develop comprehensive understanding and predictive capability to manage coastal waters of the region.

References

Adams, E.E., J.W. Hansen, R.L. Lago, P. Clayton, and X. Zhang. 1992. A simple box model of the nitrogen cycle in Boston Harbor and the Massachusetts Bays. *Civil Engineering Practice,* Fall 1992.

Christensen, J.P, D.W. Townsend, and J.P. Montoya. 1996. Water column nutrients and sedimentary denitrification in the Gulf of Maine. *Continental Shelf Research* 16: 489-515.

Doering, P.H. and C. T. Roman. 1994. Nutrients in Somes Sound and the associated watershed of Mount Desert Island, Maine. Tech. *Rept. NPS/NAROSS/NRTR-94-22,* Dept. of the Interior, National Park Service, North Atlantic Region, 15 State Street, Boston MA 02109-3572.

Garside, C., G. Hull, and C.S. Yentsch. 1978. Coastal source waters and their role as a nitrogen source for primary production in an estuary in Maine. In *Estuarine Interactions,* ed. Martin L. Wiley, 565-575, New York: Academic Press.

Geyer, W.R. and R.P. Signell. 1992. A reassessment of the role of tidal dispersion in estuaries and bays. *Estuaries* 15(2): 97-108.

Geyer, W.R., G.B. Gardner, W.S. Brown, J. Irish, B. Butman, T. Loder, and R. Signell. 1992. Physical oceanographic investigation of Massachusetts and Cape Cod Bays. *Final Report to Massachusetts Bays Program (MBP-92-03).* Boston, Massachusetts. 497 pp.

Hydroqual. 1995. A water quality model for Massachusetts and Cape Cod Bays: Calibration of the Bays Eutrophication Model (BEM). *MWRA Environ. Quality Dept. Tech. Rpt. Series,* No. 95-8. Massachusetts Water Resources Authority, Boston MA. 402 pp.

Kelly, J.R. 1991. Nutrients and Massachusetts Bay: A synthesis of eutrophication issues. *MWRA Environ. Quality Dept. Tech. Rpt. Series,* No. 91-10. Massachusetts Water Resources Authority, Boston MA. 66 pp.

Kelly, J.R. 1993. Nutrients and Massachusetts Bay: An update of eutrophication issues. *MWRA Environ. Qual. Dept. Tech. Rpt. Series,* No. 93-17 Massachusetts Water Resources Authority, Boston, MA. 119 pp.

Kelly, J. R. 1997. Nitrogen flow and the interaction of Boston Harbor with Massachusetts Bay. *Estuaries* 20(2): 365-380.

Kelly, J.R., V.M. Berounsky, S.W. Nixon, and C.A. Oviatt. 1985. Benthic-pelagic coupling and nutrient cycling across an experimental eutrophication gradient. *Marine Ecology Progress Series* 26: 207-219.

Kelly, J.R., C. S. Albro, and W.R. Geyer. 1995. High-resolution mapping studies of water quality in Boston Harbor and Massachusetts Bay during 1994. *MWRA Environ. Qual. Depart. Tech. Rpt Series,* No. 95-22, Massachusetts Water Resources Authority, Boston MA 02129. 160 pp.

Kelly, J.R. and J.T. Turner, 1995a. Water column monitoring in Massachusetts and Cape Cod Bays: Annual report for 1993. *MWRA Environ. Quality Tech. Rpt. Series,* No. 95-16. Massachusetts Water Resources Authority, Boston, MA. 162 pp.

Kelly, J.R. and J.T. Turner, 1995b. Water column monitoring in Massachusetts and Cape Cod Bays: Annual report for 1994. *MWRA Environ. Quality Tech. Rpt. Series,* No. 95-17. Massachusetts Water Resources Authority, Boston, MA. 163 pp.

Kelly, J.R. and P.H. Doering. 1995. Nutrient issues update 1995: Metabolism in Boston Harbor, Massachusetts and Cape Cod Bays, MA (USA) during 1992-1994. *MWRA Environ. Quality Tech. Rpt. Series,* No. 95-19. Massachusetts Water Resources Authority, Boston, MA. 38 pp.

Kelly, J.R. and P.H. Doering. 1996. Monitoring and modeling primary production in coastal waters: studies in Massachusetts Bay 1992-1994. *Marine Ecology Progress Series* (to appear).

Kelly, J.R. and P.S. Libby. 1996a. Dissolved oxygen in Maine Estuaries and Embayments. *Report to Wells National Estuarine Research Reserve,* Wells ME 04090. 32 pp.

Kelly, J.R. and P.S. Libby. 1996b. Dissolved oxygen in Maine Estuaries and Embayments: Detailed analysis of the influence of stratification on DO. *Addendum Report to Wells National Estuarine Research Reserve,* Wells, ME 04090. 20 pp.

Larsen, P.F. 1992. Marine environmental quality in the Gulf of Maine: a review. Reviews in *Aquatic Sciences* 6(1):67-87.

Nixon, S.W. 1983. Estuarine ecology — a comparative and experimental analysis using 14 estuaries and the MERL microcosms. *Final Report to United States Environmental Protection Agency, Chesapeake Bay Program under Grant No. X-003259-01.*

Nixon, S. W. 1992. Quantifying the relationship between nitrogen input and the productivity of marine ecosystems. *Pro. Adv. Mar. Tech. Conf.* 5:57-83.

Nixon, S. W. 1995. Coastal marine eutrophication: A definition, social causes, and future concerns. *Ophelia* 41: 199-219.

Nixon, S.W., M.E. Q. Pilson, C.A. Oviatt, P. Donaghay, B. Sullivan, S. Seitzinger, D. Rudnick and J. Frithsen. 1984. Eutrophication of a coastal marine ecosystem— an experimental study using the MERL microcosms. 105-135, In *Flows of energy and materials in marine ecosystems,* ed. M.J.R. Fasham, New York: Plenum Publishing Corporation.

Nixon S. W., C. A. Oviatt, J. Frithsen, and B. Sullivan. 1986. Nutrients and the productivity of estuarine and coastal marine ecosystems. *Journal of Limnological Society South Africa* 12: 43-71.

Nixon, S.W. , S.L. Granger, and B.L. Nowicki. 1995. An assessment of the annual mass balance of carbon, nitrogen, and phosphorus in Narragansett Bay. *Biogeochemistry* 31: 15-61.

Nixon, S.W., J.W. Ammerman, L. P. Atkinson, V.M. Berounsky, G. Billen, W. C. Boicourt, W.R. Boynton, T.M. Church, D.M. DiToro, R. Elmgren, J.H. Garber, A.E. Giblin, R.A. Jahnke, N.J.P. Owens, M.E.Q. Pilson, and S.P. Seitzinger. 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. *Biogeochemistry* 35: 141-180.

Nowicki, B. L., J.R. Kelly, E. Requintina, and D. Van Keuren. 1997. Nitrogen losses through sediment denitrification in Boston Harbor and Massachusetts Bay. *Estuaries* 20(3): 626-639.

Signell, R.P. and B. Butman. 1992. Modeling tidal exchange and dispersion in Boston Harbor. *J. Geophys. Research* 97: 15,1591-15,606.

Signell, R.P., H.L. Jenter, and A.F. Blumberg. 1996. Circulation and effluent dilution modeling in Massachusetts Bay: Model implementation, verification and results. *U.S.G.S. Open File Report 96-015.* Woods Hole MA. 121 pp.

Stommel, H. and H.G. Farmer. 1952. On the nature of estuarine circulation, Part II. *Woods Hole Oceanogr. Inst Tech. Rep.* WHOI-52-51, Woods Hole, MA.

Biological Effects of Toxic Chemical Contaminants in the Gulf of Maine

Judith E. McDowell
Woods Hole Oceanographic Institution

Environmental concern of contaminant input to coastal waters is focused on: (1) the accumulation and transfer of metals and organic contaminants in marine food chains, including accumulation in commercial resources and potential impacts on human health; and (2) the toxic effects of such contaminants on the survival and reproduction of marine organisms and the resulting impact on marine ecosystems. Evaluation of the fate and effects of toxic contaminants of environmental concern in the marine environment requires an understanding of (l) the temporal and spatial distribution of contaminants; (2) the partitioning of contaminants to different compartments of the ecosystem (e.g., sediments and biota), including assessment of contaminant bioavailability; and (3) the level of damage imposed by accumulation of contaminants in biotic resources. Such an evaluation requires the development of risk assessment or characterization that couples an understanding of contaminant distribution in the environment with an understanding of the mechanisms of toxic action and the transfer of contaminants to the human consumer. A conceptual model for describing ecological and human health risks must successfully relate contaminant distribution and bioavailability to the probability and magnitude of biological impact. The use of environmental indicators within the context of this conceptual model allows predictions of the temporal and spatial scales of environmental quality issues.

Contaminant Distributions in the Gulf of Maine

There are numerous data sets from coastal waters in the Gulf of Maine on the distribution of chemical contaminants in sediments and shellfish. Trace metals, chlorinated pesticides, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) are found in sediments and biota throughout the Gulf of Maine ecosystem (Larsen, 1992). Spatial gradients of contamination are delineated with nearshore, urban and industrialized areas having higher concentrations of specific contaminants than offshore areas.

Trace Metals

High concentrations of several trace metals have been detected in sediment samples from several estuaries within the Gulf of Maine. Chromium concentration in the Great Bay estuary (NH), the Saco River (ME), and Salem Harbor (MA) have been attributed to the input of tannery wastes to coastal waters over the past fifty years (Capuzzo and Anderson, 1973; Armstrong et al., 1976; Mayer and Fink, 1980; NOAA, 1991). Concentrations of other trace metals also appear to be elevated at several locations within the Gulf of Maine, including Boothbay Harbor, Casco Bay and Penobscot Bay (Larsen, 1992). From data sets collected in the NOAA National Status and Trends Program, several sites within the Gulf of Maine had high concentrations of trace metals (greater

than one standard deviation above the geometric mean for all stations; NOAA, 1991):
1. Merriconeag Sound for tin;
2. Cape Ann for lead and tin;
3. Salem Harbor for silver, cadmium, chromium, copper, mercury, lead, tin and zinc;
4. Boston Harbor for silver, cadmium, chromium, mercury, lead and tin;
5. Quincy Bay for silver, cadmium, chromium, copper, mercury, lead and tin.

For biological samples, differences in background trace metal levels between species of organisms can be as large as several orders of magnitude; whereas trace metal levels in the same species sampled along an environmental gradient from uncontaminated to contaminated habitats may vary by less than an order of magnitude. Marine animals differ in their capacity to store, remove and detoxify metal contaminants. Thus, considerable variation in metal content may be apparent among different species collected from a single location. Seasonal differences in metal concentrations in *Mytilus* vary by a factor of 2 to 4 due to changes in physiological and/or reproductive condition (Capuzzo et al., 1987).

Samples collected and analyzed during the U.S. Mussel Watch Program (1976 to 1978) indicate a relatively high concentration of lead in mussels collected at several New England sites ranging from Cape Newagen, ME, to Cape Cod Canal, MA, with the highest concentrations occurring at Cape Ann and Boston, MA (Goldberg et al., 1983). Among the NOAA National Status and Trends Mussel Watch stations, several sites surveyed in the Gulf of Maine were among the twenty most contaminated sites in U.S. coastal waters for several trace metals (NOAA, 1989):
1. Boston Harbor for silver, lead, mercury, copper and chromium;
2. Salem Harbor for lead, copper and chromium; and
3. Penobscot Bay for mercury.

Results from the pilot program for Gulfwatch indicate high concentrations of lead in mussels from Boothbay Harbor, ME (Sowles et al., 1992).

Petroleum Hydrocarbons and Chlorinated Hydrocarbons

Petroleum hydrocarbons may be derived from a variety of different sources including the burning of fossil fuels, accidental oil spills, and chronic inputs from municipal discharges and marinas. Oil spills have occurred frequently in the Gulf of Maine, especially in Boston Harbor, Portland Harbor, and Penobscot Bay. Sites in the Gulf of Maine with high concentrations of polycyclic aromatic hydrocarbons include Boston Harbor, Casco Bay and Penobscot Bay. Loadings of PAHs to Massachusetts Bay are estimated to be within the range of 2.1 to 13.7 metric tons per year (Menzie-Cura & Associates, 1991). Sites receiving inputs from combined sewer overflows (CSOs) are among the most contaminated sites in Boston Harbor/Massachusetts Bays. Concentrations of total PAHs in Boston Harbor sediments are among the highest reported for all coastal sites of the U.S. in the NOAA National Status and Trends program. Among sites examined within the New England region, concentrations of total PAHs in sediment samples from Boston Harbor exceeded concentrations in samples from other sites by as much as one to two orders of magnitude (MacDonald, 1991).

Johnson et al. (1985) reported high concentrations of PAHs in Penobscot Bay, with a distinct spatial gradient decreasing seaward from the head of the bay. The composition of PAHs suggested a pyrogenic source and the authors concluded that atmospheric transport and river runoff may be the major sources of PAH contamination. Larsen et al. (1983) reported high concentrations of PAHs in Casco Bay with the highest levels found in Portland Harbor and the composition reflecting multiple sources of input including automobile and aircraft traffic, petroleum handling facilities, and municipal sewer systems. Additional studies in the central Gulf of Maine suggested an accumulation of PAHs in the fine grained sediments in depositional basins (Larsen et al., 1986).

Among the NOAA National Status and Trends sediment stations, several sites in the Gulf of Maine had high concentrations of low molecular weight (2- and 3-ring) compounds and high molecular weight (4-ring and larger) compounds (NOAA, 1991):
1. Penobscot Bay - low molecular weight and high molecular weight aromatic hydrocarbons;
2. Casco Bay (Kennebec River) - low molecular weight aromatic hydrocarbons;

3. Cape Ann - high molecular weight aromatic hydrocarbons;
4. Salem Harbor - low molecular weight and high molecular weight aromatic hydrocarbons;
5. Boston Harbor - low molecular weight and high molecular weight aromatic hydrocarbons; and
6. Quincy Bay - low molecular weight and high molecular weight aromatic hydrocarbons.

Chlorinated hydrocarbons (including DDT, other chlorinated pesticides, and polychlorinated biphenyls or PCBs) are highly resistant to degradation in the marine environment and may accumulate to high concentrations in both sediments and biota. For the few areas of the U.S. coastline for which long-term data sets exist, the concentrations of chlorinated hydrocarbons in sediments and tissues of marine organisms appear to be declining since the late 1960s and early 1970s (Mearns et al., 1988), with the exception of highly contaminated areas such as New Bedford Harbor, MA. Comparison of data for NOAA National Status and Trends Stations in the Gulf of Maine reveal that only Boston Harbor and Salem Harbor have high concentrations of total PCBs and total DDT. Data collected by Larsen et al. (1984) on PCB concentrations in sediments from Casco Bay suggest that the concentrations of PCBs have increased since the 1980s. Data summarized by Hauge (1988) and reported by Larsen (1992) suggest that agricultural runoff may contribute large inputs of chlorinated pesticides, such as aldrin, chlordane and heptachlor, to the Gulf of Maine through the Kennebec estuary. Concentrations of individual pesticides in sediments from the Kennebec River Plume are as high or higher than sediments from urban harbors such as Boston Harbor.

Lipophilic organic contaminants such as PAHs (polycyclic aromatic hydrocarbons), PCBs (polychlorinated biphenyls), and other synthetic compounds for which PAHs and PCBs serve in part as model compounds, are generally recalcitrant in the marine environment. Thus, such compounds or their metabolites may accumulate to high levels in animal tissues and interfere with normal metabolic processes that affect growth, development, and reproduction (Capuzzo et al., 1988). The bioavailability, bioconcentration, and toxic effects of lipophilic contaminants are related to their pharmacological and toxicological properties (Capuzzo, 1987; Widdows et al., 1987; Abernathy et al., 1986; Donkin et al., 1990). The limited capacity of bivalve molluscs to detoxify organic contaminants (Stegeman, 1985; Livingstone and Farrar, 1984) results in the uptake and accumulation of high concentrations of organic contaminants.

Because of the hydrophobic properties of individual lipophilic organic contaminants, these contaminants readily sorb to particles. Thus, once introduced to aquatic systems, lipophilic organic contaminants become associated with sediment deposits and may be readily accumulated by benthic organisms. Transfer of contaminants to marine biota and the human consumer and toxicological effects on the ecosystem are dependent on the availability and persistence of these contaminants within benthic environments.

The bioaccumulation of lipophilic organic contaminants is influenced by chemical factors such as solubility and particle adsorption-desorption kinetics of specific compounds; and biological factors such as the transfer of compounds through food chains and the amount of body lipid in exposed organisms. Differences in contaminant concentrations among species from different habitats may be the result of differences in the availability of sediment-bound contaminants and capacity for biotransformation. In contrast to body burdens of trace metals, differences in the concentration of lipophilic organic contaminants in bivalves collected from uncontaminated and contaminated locations may vary by several orders of magnitude (Capuzzo et al., 1987).

Samples of mussels taken during the U.S. Mussel Watch Program (1976 to 1978) indicate that shellfish collected from the northeastern part of the U.S. had elevated concentrations of PCBs in comparison with shellfish collected from U.S. west coast sites (Farrington et al., 1983). The lowest levels of PCBs in the northeast were detected in mussels collected from the Maine coast (with the exception of Portland, Casco Bay) and stations north of Boston. Consistently elevated levels (> 0.01 ppm wet weight) were evident from Boston southward. The highest levels of PCBs (by several orders of magnitude) were detected in mussels collected at New Bedford Harbor. Concentrations of PAHs in mussels were generally < 0.1 ppm wet weight, with the exception of samples collected from Boston Harbor where values ranged from 0.3 to 0.5 ppm wet weight.

Among the NOAA National Status and Trends Mussel Watch stations, several sites surveyed in the

Table1.
National Status and Trends Mussel Watch Data

General Site Specific Site	Cd	Cr	Cu	Pb	Hg	Ag	Zn	tDDT	tCdane	tPCB
Maine										
Penobscot Bay										
Sears Island										
Pickering Island					*					
Merriconeag Sound										
Stover Point										
Cape Arundel										
Kennebunkport										
Massachusetts										
Cape Ann										
Gap Head										
Salem Harbor										
Folger Point		**		**						
Boston Harbor										
Deer Island				*	*	*		*		
Dorchester Bay				**	*	*		*	*	
Hingham Bay				*		*		*	*	
Brewster Island				*	*					
Duxbury Bay										
Clarks Island					*					
Cape Cod Bay										
Nauset Harbor										

Source: Gottholm and Turgeon, 1992
Note: * High concentration, more than the mean plus 1 S.D. of log normal distribution of all sites
** Very high concentration, more than the mean plus 2 S.D. of log normal distribution of all sites

Gulf of Maine were among the twenty most contaminated sites in U.S. coastal waters for PAHs and chlorinated hydrocarbons (Table 1, NOAA, 1989; Gottholm and Turgeon, 1992):

1. Boston Harbor for low molecular weight and high molecular weight aromatic hydrocarbons, total DDT, total PCBs, lindane, dieldrin, and total chlordane;
2. Salem Harbor for dieldrin;
3. Merriconeag Sound for lindane; and
4. Penobscot Bay for lindane.

In the Gulfwatch Program, mussels from Boothbay Harbor had high concentrations of PCBs and PAHs (Sowles et al., 1992).

Sediments and biota from Boston Harbor are highly contaminated with a variety of lipophilic organic contaminants including petroleum hydrocarbons (both low molecular weight and high molecular weight hydrocarbons such as PAHs), chlorinated pesticides (total DDT, lindane, dieldrin and chlordane), and polychlorinated biphenyls (PCBs). For example, concentrations of total PAHs in tissues of the blue mussel (*Mytilus edulis*) are in the upper 15% of the most contaminated sites from the U.S. coastline (MacDonald, 1991). Other contaminants that show elevated levels in mussels collected from Boston Harbor include total DDT, total PCBs, lindane, dieldrin, and total chlordane.

Although the data sets are much less extensive other biological samples have been collected as part of national or regional monitoring programs and analyzed for trace contaminants. The largest data set is that for trace contaminants in fish livers collected as part of the NOAA National Status and Trends Benthic Surveillance program. A comparison of trace metal concentrations in fish liver samples taken from 1984 to 1987 at the same sites as sediment samples were collected indicated a gradient of trace metal contamination throughout the Gulf of Maine with moderate to high concentration of individual trace metals being detected in samples from Casco Bay, Boston Harbor, Salem Harbor and Quincy Bay (NOAA, 1987). For lipophilic organic contaminants, samples from Boston Harbor and Quincy Bay have the highest concentrations of total DDT, other chlorinated hydrocarbons and total PCBs (Gottholm and Turgeon, 1992).

Biological Effects of Contaminants

Although general trends in contaminant distributions in urban areas and adjacent waters of the Gulf of Maine ecosystem, such as Boston Harbor/Massachusetts Bays, have been defined (e.g., higher concentrations of total PAHs in the inner harbor of Boston, lesser concentrations with distance from the inner harbor), critical information on biological effects of chemical contaminants, specifically on population processes is lacking. Because harbor sediments will continue to be a major source of contaminants to the Massachusetts and Cape Cod Bays ecosystem, even with the improvement in water quality from the reduction of point source contamination, the potential risks to populations of marine biota must be defined.

Ecological concerns of contamination in the marine environment include changes in species distributions and abundance, habitat alterations, and changes in energy flow and biogeochemical cycles. The toxic effects of chemical contaminants on marine organisms are dependent on bioavailability and persistence, the ability of organisms to accumulate and metabolize contaminants, and the interference of contaminants with specific metabolic or ecological processes. Recent studies of the incidence of tumors and other histopathological disorders in bottom-dwelling fish and shellfish from contaminated coastal areas have suggested a possible link between levels of lipophilic organic contaminants and the increased incidence of histopathological conditions. Unpublished data by Sherburne (reported by Larsen, 1992) suggests a high incidence of several histopathological disorders in fish, crabs and clams from contaminated areas along the coast of Maine. The occurrence of liver neoplasia in adult winter flounder (Murchelano and Wolke, 1985) and the progression of abnormal cell types in the liver of young winter flounder (Moore, 1991) have been observed along a contaminant gradient in Boston Harbor and Massachusetts Bay. Chemical associated liver disease at these sites has been correlated with exposure to polycylic aromatic hydrocarbons and halogenated aromatic hydrocarbons (Gardner et al., 1989; Johnson et al., 1993). Moore et al. (1996) examined temporal trends in liver lesions in winter flounder populations from Boston Harbor/Massachusetts Bay in relation to changes in water quality associated with improvements in waste water treatment and contaminant source control. A marked decline in prevalence in liver neoplasia was observed during the period 1987 to 1993; this decline correlated with a reduction in contaminant input to the Deer Island waste water treatment plant. Hydropic vacuolation in livers from winter flounder populations in the vicinity of Deer Island continued to remain at high levels and correlated with high levels of chlorinated hydrocarbons in liver samples.

Gardner et al. (1991) reported the prevalence of germinomas and other histopathological disorders in soft shell clam populations from three sites along the Maine coast - Searsport, Penobscot Bay; and Roque Bluffs, Machiasport; and Dennysville. He suggested that these aberrations were not associated with petroleum hydrocarbon exposure as previously suggested (Barry and Yevich, 1975) but linked to herbicide use in blueberry agriculture and silviculture. Present-day studies indicate continued high prevalence of gonadal tumors in clam populations even though herbicide practices have changed during the past two decades (Van Beneden, U. Maine, Orono, ME, personal communication). Van Beneden et al. (1993) isolated DNA from epizootic seminomas and dysgerminomas from clam populations in Maine and used NIH3T3 transfection assays to determine the presence of activated oncogenes. The results indicated that DNA from clam tumors was capable of transforming mouse fibroblasts. Brown et al. (1996) reported a dioxin-specific binding protein in clams from the same contaminated sites in Maine and suggest a possible relationship with the high prevalence of gonadal tumors.

Gardner and Pruell (1988) found significant histopathological lesions in soft shell clams *(Mya arenaria)* at selected contaminated sites in Quincy Bay including gill inflammation, atypical cell hyperplasia in gill and kidney, hyperparasitism with rickettsia in digestive ducts/tubules, and general parasitism. Recent studies conducted by Moore et al. (1995) in Massachusetts and Cape Cod Bays revealed a suite of histopathological conditions associated with chemical contaminant exposure in fish and shellfish. Populations of *Mya arenaria* and *Mytilus edulis* collected along a gradient of PAH contamination showed evidence of a wide range of pathologies including gill hyperplasia and carcinomas, hematopoietic neoplasia, gonadal inflammation, parasitic infections in connective tissues and kidney, and kidney hyperplasia. Discriminant analysis indicated that the prevalence of these pathologies was strongly correlated with high levels of PAH contamination.

In addition to histopathological damage, sublethal toxic effects of contaminants in marine organisms include impairment of physiological processes that may alter the energy available for growth and reproduction and other effects on reproductive and developmental processes including direct genetic damage. Biological effects associated with bioconcentration of lipophilic contaminants have been attributed to the uptake of specific compounds and/or their metabolites, rather than the total body burden of hydrocarbons or chlorinated hydrocarbons (Anderson et al., 1980; Malins and Hodgins, 1981; Widdows et al., 1982, 1987; Capuzzo et al., 1984). Biological effects of organic contaminants have been observed at all levels of biological hierarchy (McIntyre and Pearce, 1980; Capuzzo, 1987; Moore et al., 1989). An understanding of reproductive and developmental processes provides the critical link between responses to contaminants at the organismal and suborganismal levels and population consequences. Alterations in bioenergetics linked with observations of reduced fecundity and viability of larvae, abnormalities in gamete and embryological development, and reduced reproductive success provide a strong empirical basis for examination of population responses.

For bivalve molluscs (including populations in the Gulf of Maine), exposure to contaminants has resulted in impairment of physiological mechanisms (Capuzzo and Sasner, 1977; Gilfillan et al., 1977); histopathological disorders (Moore et al., 1995; McDowell and Shea, 1996); and loss of reproductive potential (McDowell and Shea, 1996). Gilfillan et al. (1977) observed a strong correlation between tissue concentrations of aromatic hydrocarbons and reductions in carbon flux in clam populations (*Mya arenaria*) from oil contaminated sites in Maine. Gardner and Pruell (1988) observed asynchronous reproductive development and spawning among male and female clams in Quincy Bay, Massachusetts. Kimball (1994) also observed asynchrony in reproductive development among three populations of *Mytilus edulis* in Massachusetts and Cape Cod Bays, but the reductions in reproductive effort among female mussels could not be attributed to the effects of contaminants alone.

McDowell and Shea (1996) examined the effects of lipophilic organic contaminants on population processes in the soft shell clam *Mya arenaria*, collected along a gradient of polycyclic aromatic hydrocarbon contamination in Boston Harbor and Massachusetts and Cape Cod Bays. Contaminants were detected in clam tissues and sediments but the bioavailability of specific compounds varied at different sites. Clam populations at the three most contaminated sites (Fort Point Channel, Saugus River and Neponset River) showed similar patterns in lipid accumulation in the digestive gland-gonad complex and similar patterns in reproductive development. Highest levels of reproductive output were observed among clam populations from uncontaminated sites. High prevalence of hematopoietic neoplasia and gonadal inflammation were observed among clam populations from the three most contaminated sites, specially at Fort Point Channel. Population processes of clam populations at all sites were compared using a deterministic matrix population model. Site features in addition to contaminant levels strongly influenced population growth with high inter-site and inter-annual variability in processes such as recruitment and survival being observed (Ripley, WHOI, unpublished data).

Human Health Concerns

The transfer of toxic chemicals through marine food chains can result in bioaccumulation in commercial fishery resources and transfer to the human consumer. Of specific concern is the uptake and transfer of metals, halogenated hydrocarbons, and other organic contaminants including petroleum hydrocarbons derived from accidental oil spills, municipal discharges and urban runoff. Contaminants that demonstrate mutagenic, carcinogenic, or teratogenic potential to the human consumer are of particular concern because they pose direct threats to human health.

Chemical contamination of fishery resources has recently led to fishery closures or fishery advisories in several areas of the U.S. coastline (Capuzzo et al., 1987). For example, striped bass fisheries in the states of New York and Rhode Island were closed in 1986 as a result of PCB contamination; the State of California developed health advisories warning the public against frequent consumption of fish caught in southern California waters; in 1988 the Department of Public Health in the Commonwealth of Massachusetts issued a state-wide advisory on the consumption of lobster tomalley (hepatopancreas) because of the exceedingly high levels of PCBs and other contaminants; and in 1994 health officials in Maine issued a health advisory for nursing mothers, pregnant women, and women of child-bearing age on the consumption of lobster tomalley because of dioxin levels. In addition, health advisories for the consumption of freshwater fish have been issued in Maine because of dioxin contamination (1990) and in Massachusetts because of mercury contamination (1994). In Buzzards Bay, MA, approximately 28 square miles are closed to finfishing and shellfishing as a result of PCB contamination. These recent actions illustrate a growing concern for the impact of chemical contamination on resources in coastal waters.

Monitoring and Management Needs

Sediment contaminant concentrations do not easily translate to biological concerns as bioavailability and toxicological properties can vary widely. Few sediment reference criteria are available; however, concentrations of several contaminants, especially in specific embayments, are high enough to elicit concern of potential biological effects and exceed the ER-M values developed by Long and Morgan (1990) as guidelines for evaluating sediment contamination. As the relationships between levels of chemical contaminants and biological responses in fish and shellfish continue to be explored, insight of the toxic action of specific compounds and groups of compounds are being elucidated. However, our knowledge of cause and effect relationships between tissue burdens of many contaminants and biological consequences in many species is still incomplete. A broad regional assessment of biological effects of contaminants in the Gulf of Maine ecosystem is lacking at the present time.

Monitoring programs for measuring the fate and effects chemical contaminants in coastal ecosystems should be designed and executed to provide meaningful information on: (1) spatial distribution of contaminants; (2) temporal variability in contaminant distributions, as a result of both natural variability and changes in chemical use patterns or pollution abatement; and (3) the relationship of contaminant inputs to ecological consequences, including habitat alterations of valuable resources, and human health concerns. Current state and federal monitoring efforts in the Gulf of Maine, however, are too limited in scope (both spatially and temporally) to meet these goals.

Ecological effects of contaminants in coastal environments include impairment of feeding, growth, development, and recruitment that may result in both alterations in reproductive and developmental success and changes in community structure and dynamics. The human health concerns of contaminated resources are obvious. Yet, it is difficult to ascertain the relationship between chronic responses of organisms to contaminated habitats and large-scale alterations in the functioning of marine ecosystems as well as large-scale contamination of fishery resources. The sensitivity of early developmental stages, the impairment of reproductive processes, and the long-term effects on populations suggest that chronic exposure to many contaminants may certainly alter the dynamics of populations, including populations of valuable commercial resources.

To better understand the fate and potential effects of contaminants in the Gulf of Maine ecosystem, the following parameters need to be evaluated:

1. Define the sources of contamination for specific contaminants - what is the relative contribution of different point and non-point sources to loading of individual compounds? An inventory of every compound is not feasible but an assessment of a few highly persistent compounds such as PCBs, PAHs, and the polychlorinated dibenzodioxins (PCDDs) should be possible.
2. Determine the persistence, degradation rates, and biogeochemical cycling of specific contaminants in sediments at selected sites in the Gulf of Maine ecosystem. How does the flux of specific compounds and the body burdens of resident organisms vary with site?

3. Using populations of indigenous bivalve species or demersal fish or lobster populations during seasons with limited migrations, define patterns of contaminant exposure and the relationship between exposure and changes in physiological condition or other parameters of biological change.

Such a program could lead to a better understanding of the causal relationship between input of specific contaminants and the relative ecological and human health risks associated with such inputs. Specific management issues that must be addressed, especially in consideration of the ecological and human health risks associated with chemical contamination, are the development of contaminant guidelines for benthic habitats. These should include consideration of guidelines for the disposal of contaminated dredged materials, development of interim sediment criteria, and the routine determination of concentrations of contaminants in harvestable resource species.

At a recent workshop on science and policy interactions in the Gulf of Maine convened by the National Research Council (NRC, 1995), it was recommended that the results of monitoring programs be communicated to as many audiences as possible, including policy makers, regulators, the public, and other stakeholders. Improved communication of monitoring results provides several benefits including better integration of scientific information into the policy and management process in addition to developing a better understanding by the general public on the scope of the issues of environmental concern. To simultaneously meet the policy and legal requirements of monitoring programs and the scientific rigors of hypothesis testing leading to a better understanding of cause and effect relationships, the selection of appropriate environmental indicators must be made by both scientists and policy makers.

References

Abernathy, S., A. M. Bobra, W. Y. Shiu, P. G. Wells, and D. Mackay. 1986. Acute lethal toxicity of hydrocarbons and chlorinated hydrocarbons to two planktonic crustaceans: The key role of organism-water partitioning. *Aquat. Toxicol.* 8:163-174.

Anderson, J. W., S. L. Kiesser, and J. W. Blaylock. 1980. The cumulative effect of petroleum hydrocarbons on marine crustaceans during constant exposure. *Rapp. P. v. Reun. Cons. Int. Explor. Mer* 179:62-70

Armstrong, P. B., G. M. Hanson, and H. E. Gaudette. 1976. Minor elements in sediments of Great Bay estuary, New Hampshire. *Environ. Geol.* 1:207-214.

Barry, M. and P. P. Yevich. 1975. The ecological, chemical and histopathological evaluation of an oil spill site. III. Histopathological studies. *Mar. Pollut. Bull.* 6:164-173.

Brown, D. J., G. C. Clark, G. R. Gardner and R. J. VanBeneden. 1996. Identification of dioxin-specific binding proteins in marine bivalves. *Mar. Environ. Res.* 42:7-11.

Capuzzo, J. M. 1987. Biological effects of petroleum hydrocarbons: Assessments from experimental results. In *Long-term Environmental Effects of Offshore Oil and Gas Development*, eds. D. F. Boesch and N. N. Rabalais 343-410. London: Elsevier Applied Science.

Capuzzo, J. McDowell, M. N. Moore, and J. Widdows. 1988. Effects of toxic chemicals in the marine environment: Predictions of impacts from laboratory studies. *Aquat. Toxicol.* 11:303-311.

Capuzzo, J. McDowell, A. E. McElroy, and G. Wallace. 1987. Fish and Shellfish Contamination in New England Waters: An Evaluation and Review of Available Data on the Distribution of Chemical Contaminants. Report for the Coast Alliance, Washington, DC, 59 pp plus appendices.

Capuzzo, J. M., B. A. Lancaster and G. C. Sasaki. 1984. The effects of petroleum hydrocarbons on lipid metabolism and energetics of larval development and metamorphosis in the American lobster (*Homarus americanus Milne Edwards*). *Marine Environmental Research* 14:201-228.

Capuzzo, J. M. and J. J. Sasner. 1977. The effect of chromium on filtration rates and metabolic activity of *Mytilus edulis* L. and *Mya arenaria* L. In *Physiological responses of marine biota to pollutants*, eds. F. J. Vernberg, A. Calabrese, F. P. Thurberg and W. B. Vernberg, 225-237. New York: Academic Press.

Capuzzo, J. M. and F. E. Anderson. 1973. The use of modern chromium accumulations to determine estuarine sedimentation rates. *Marine Geology* 14:225-235.

Donkin, P., J. Widdows, S. V. Evans, C. M. Worrall, and M. Carr. 1990. Quantitative structure-activity relationships for the effect of hydrophobic chemicals on rate of feeding by mussels (*Mytilus edulis*). *Aquat. Toxicol.* 14:277-294.

Farrington, J. W., E. D. Goldberg, R. W. Risebrough, J. H. Martin, and V. T. Bowen. 1983. U.S. "Mussel Watch" 1976-1978: An overview of the trace metal, DDE, PCB, hydrocarbon and artificial radionuclide data. *Environ. Sci. Technol.* 17:490-496.

Gardner, G. R., P. P. Yevich, J. Hurst, P. Thayer, S. Benyi, J.C. Harshbarger, and R. J. Pruell. 1991. Germinomas and teratoid siphon anomalies in softshell clams, *Mya arenaria*, environmentally exposed to herbicides. *Environmental Health Perspectives* 90:43-51.

Gardner, G. R., R.J. Pruell, and L.C. Folmar. 1989. A comparison of both neoplastic and non-neoplastic disorders in winter flounder (*Pseudopleuronectes americanus*) from eight areas in New England. *Mar. Environ. Res.* 28: 393-397.

Gardner, G. R. and R. J. Pruell. 1988. A histopathological and chemical assessment of winter flounder, lobster and soft-shelled clam indigenous to Quincy Bay, Boston Harbor and an *in situ* evaluation of oysters including sediment (surface and cores) chemistry. U.S. Environmental Protection Agency, Environmental Research Laboratory, Narragansett, RI.

Gilfillan, E. S., D. W. Mayo, D. S. Page, D. Donovan, and S. Hanson. 1977. Effects of varying concentrations of petroleum hydrocarbons in sediments on carbon flux in Mya arenaria. In *Physiological responses of marine biota to pollutants*, ed. F. J. Vernberg, A. Calabrese, F. P. Thurberg and W. B. Vernberg, 299-314. New York: Academic Press.

Goldberg, E. D., M. Koide, V. Hodge, A. R. Flegal, and J. Martin. 1983. U.S. Mussel Watch: 1977-78 results on trace metals and radionuclides. *Est. Coast. Shelf Sci.* 16:69-93.

Gottholm, B. W. and D. D. Turgeon. 1992. Toxic contaminants in the Gulf of Maine. NOAA, Coastal Monitoring and Bioeffects Division, Rockville, MD.

Hauge, P. 1988. Troubled waters: Report on the environmental health of Casco Bay. Conservation Law Foundation, Boston, MA, 71 pp.

Johnson, A. C., P. F. Larsen, D. F. Gadbois, and A. W. Humason. 1985. The distribution of polycyclic aromatic hydrocarbons in the surficial sediments of Penobscot Bay (Maine, USA) in relation to possible sources and to other sites worldwide. *Mar. Environ. Res.* 15:1-16.

Johnson, L. L., C. M. Stehr, O. P. Olson, M. S. Myers, S. M. Pierce, C. A. Wigren, B. B. McCain and U. Varanasi. 1993. Chemical contaminants and hepatic lesions in winter flounder (*Pleuronectes americanus*) from the northeast coast of the United States. *Env. Sci. Technol.* 27: 2759-2771.

Kimball, D. M. 1994. The reproductive cycle in three populations of the blue mussel, *Mytilus edulis*, from Boston Harbor and Cape Cod Bay. Ph.D. Dissertation, University of Massachusetts-Boston, Boston, MA.

Larsen, P. F. 1992. Marine Environmental Quality in the Gulf of Maine: A Review. *Reviews in Aquatic Sciences* 6:67-87.

Larsen, P. F., D. F. Gadbois, and A. C. Johnson. 1986. Distribution of polycylic aromatic hydrocarbons in surficial sediments of the deeper waters of the Gulf of Maine. *Mar. Pollut. Bull.* 18:231-244.

Larsen, P. F., D. F. Gadbois, A. C. Johnson, and R. F. Maney. 1984. On the appearance of PCBs in the surficial sediments of Casco Bay, Maine. *Mar. Pollut. Bull.* 15: 452-453.

Larsen, P. F., D. F. Gadbois, A. C. Johnson, and L. F. Doggett. 1983. Distribution of polycyclic aromatic hydrocarbons in the surficial sediments of Casco Bay, Maine. *Bull. Environ. Contam. Toxicol.* 30:530-535.

Livingstone, D. R. and S. V. Farrar. 1984. Tissue and subcellular distribution of enzyme activities of mixed-function oxygenase and benzo[a]pyrene metabolism in the common mussel *Mytilus edulis* L. *Sci. Tot. Environ.* 39:209-235.

Long, E. R. and L. G. Morgan. 1990. The potential for biological effects of sediment-sorbed contaminants tested in the National Status and Trends Program. NOAA Technical Memorandum NOS OMA 52. NOAA, Office of Oceanography and Marine Assessment, Ocean Assessments Division, Seattle, WA, 173 pp. plus appendices.

MacDonald, D. A. 1991. Status and trends in concentrations of selected contaminants in Boston Harbor sediments and biota. NOAA Technical Memorandum NOS OMA 56, Seattle, WA.

Malins, D. C. and H. O. Hodgins. 1981. Petroleum and marine fishes: A review of uptake, disposition, and effects. *Environmental Science and Technology* 15:1272-1280.

Mayer, L. M. and L. K. Fink, Jr. 1980. Granulometric dependence of chromium accumulation in estuarine sediments in Maine. *Estuar. Coast. Mar. Sci.* 11: 491-503.

McDowell, J. E. and D. Shea. 1996. Population Processes of *Mya arenaria* from Contaminated Habitats in Massachusetts Bays. Final Report to the Massachusetts Bays Program, Boston, MA.

McIntyre, A. D. and J. B. Pearce, editors. 1980. Biological Effects of Marine Pollution and the Problems of Monitoring. *Rapp. P.-V. Reun. Cons. Int. Explor Mer* 179:1-346.

Mearns, A. J., M. B. Matta, D. Simecek-Beatty, M. F. Buchman, G. Shigenaka, and W. A. Wert. 1988. PCB and chlorinated pesticide contamination in U.S. Fish and Shellfish: A historical assessment report. NOAA Technical Memorandum NOS OMA 39. National Ocean Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Rockville, MD, 139 pp.

Menzie-Cura & Associates, Inc. 1991. Sources and loadings of pollutants to the Massachusetts Bays. Report to the Massachusetts Bays Program, MBP-91-01, Boston, MA.

Moore, M. J., D. Shea, R. E. Hillman, and J. J. Stegeman. 1996. Trends in hepatic tumours and hydropic vacuolation, fin erosion, organic chemicals and stable isotope ratios in winter flounder from Massachusetts, USA. *Mar. Pollut. Bull.* 32: 458-470.

Moore, M. J., R. M. Smolowitz, D. F. Leavitt, and J. J. Stegeman. 1995. Evaluation of chemical contaminant effects in the Massachusetts Bays. Final Reprort to the Massachusetts Bays Program, Boston, MA.

Moore, M. J. 1991. Vacuolation, Proliferation and Neoplasia in the Liver of Boston Harbor Winter Flounder *(Pseudopleuronectes americanus)*. Ph.D. Dissertation, MIT/WHOI Joint Program in Biological Oceanography. Woods Hole Oceanographic Institution, Woods Hole, MA Document 91-28, 267 pp.

Moore, M. N., D. R. Livingstone and J. Widdows. 1989. Hydrocarbons in marine molluscs: Biological effects and ecological consequences. In *Metabolism of polycyclic aromatic hydrocarbons in the aquatic environment.* ed. U. Varanasi, 291-328. Boca Raton: CRC Press.

Murchelano, R. A. and R. E. Wolke. 1985. Epizootic carcinoma in winter flounder, Pseudopleuronectes americanus. *Science* 228: 587-589.

NOAA. 1991. Second summary of data on chemical contaminants in sediments from the National Status and Trends Program. NOAA Technical Memorandum NOS OMA 59, Rockville, MD.

NOAA. 1989. A summary of data on tissue contamination from the first three years (1986-1988) of the Mussel Watch Project. NOAA Technical Memorandum NOS OMA 49, Ocean Assessment Division, Office of Oceanography and Marine Assessment, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Rockville, MD, 22 pp. plus appendices.

NOAA. 1987. A summary of selected data on chemical contaminants in tissues collected during 1984, 1985, and 1986. NOAA Technical Memorandum NOS OMA 38. Ocean Assessment Division, Office of Oceanography and Marine Assessment, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Rockville, MD, 23pp. plus appendices.

NRC, 1995. Improving Interactions between Coastal Science and Policy. Proceedings of the Gulf of Maine Symposium. National Research Council, National Academy Press, Washington, DC, 259pp.

Sowles, J., R. Crawford, J. Machell, G. Atkinson, P. Hennigar, S. Jones, J. Pederson, and K. Coombs. 1992. Evaluation of Gulfwatch. 1991 Pilot Project of the Gulf of Maine Marine Environmental Monitoring Plan. The Gulf of Maine Council on the Marine Environment, 39 pp. plus appendices.

Stegeman, J. J. 1985. Benzo(a)pyrene oxidation and microsomal enzyme activity in the mussel *(Mytilus edulis)* and other bivalve mollusc species from the Western North Atlantic. *Mar. Biol.* 89:21-30.

VanBeneden, R. J., G. R. Gardner, N. J. Blake and D. G. Blair. 1993. Implications for the presence of transforming genes in gonadal tumors in two bivalve mollusk species. *J. Cancer Res.* 53: 2976-2979.

Widdows, J., P. Donkin, and S. V. Evans. 1987. Physiological responses of Mytilus edulis during chronic oil exposure and recovery. *Mar. Environ. Res.* 23:15-32.

Widdows, J., T. Bakke, B. L. Bayne, P. Donkin, D. R. Livingstone, D.M. Lowe, M. N. Moore, S.V. Evans, and S.L. Moore. 1982. Responses of Mytilus edulis on exposure to the water accommodated fraction of North Sea oil. *Mar. Biol.* 67:15-31.

Recent Advances and Challenges in Fisheries Science

Michael Sinclair
Bedford Institute of Oceanography

Introduction

The organizers of this meeting requested that I address five questions in this overview paper on recent advances and problems in fisheries science. They are:
1. What have we learned during the past five years that has improved our ability to manage fisheries?
2. What are the key scientific uncertainties with the present single species approach?
3. To what extent have recent shortfalls in management of Atlantic cod been due to poor science?
4. What have we learned about the ecosystem context for the management of harvest fisheries?
5. Would an ecosystem approach for the Gulf of Maine area be better than the present single species approach?

The first three questions dealing with the present management approach are somewhat interlocking. Questions four and five address the basic concepts underlying fisheries management. The overall sense of the questions are: do we need to reinvent fisheries management, or fix what we have? I will argue the case that it is premature to abandon the status quo approach, and that we should focus on improving the implementation of the presently used tools for controlling fishing effort and adjusting fishing capacity.

The present approach to fisheries management in the Gulf of Maine area is based on biological concepts that were introduced during the 1920s to 1950s in northern Europe, following the paradigm shift of 1914 (see Smith 1994 for an excellent history of fisheries science, and Sinclair 1996a for details on the changes in conceptual framework that arose from the work of Committee A of the International Council for the Exploration of the Sea between 1902 and 1908). The changes in the theory to account for interannual and decadal scale fluctuations in landings from marine fisheries introduced by Hjort (1914) are summarized below.

Table 1.
Paradigm Shift on Theory of Fluctuations in Fisheries Yields

Before	After
"Essentialist" species concept	"Biological" species concept
Species the unit of study	Population the unit of study
Abundance relatively constant, renewal regular	Abundance highly variable, renewal irregular
Inexhaustible abundance (over fishing impossible)	Finite abundance (overfishing likely)
Inter-annual fluctuations due to geographically variable migration of species	Inter-annual fluctuations due to year-class variability of populations

The key changes from a fisheries management perspective were that geographically constrained populations, rather than the distributional area of the species, became the relevant ecological level for understanding temporal fluctuations in landings. Also overfishing of populations is likely to occur if fishing effort is not limited. As an aside, this fisheries fluctuations theory implied a new species concept which predated by two decades the articulation of the "biological species" concept of Ernst Mayr in the so-called new synthesis within evolutionary biology (Mayr 1982). As early as 1914 Hjort identified the concept of "growth overfishing", although he did not use this term. Beverton and Holt (1957) provided an operational definition of growth overfishing, fishing mortalities above those that will generate maximum yield per recruit (Figure 1). In essence, it is these two concepts that are the biological basis of our present management approach: populations are the preferred unit for management, and yield from such populations can be maximized at some moderate level of fishing mortality that is a function of the growth rate of these species and size selectivity of the harvesting technology. Much of the stock assessment work within the Gulf of Maine area attempts to estimate absolute abundance of single species within management areas, and the appropriate fishing effort levels that will result in exploitation levels at a target consistent with conservation objectives. The approach infers that food-chain interactions between marine species do not act in an "abundance-dependent" manner, or that if they do occur in such a manner, benefits from management can be achieved without explicitly incorporating them. It is worth noting that the Beverton and Holt model does incorporate some ecosystem effects. The yield per recruit of cod on the western Scotian Shelf (4X) is about three times that estimated for the eastern Scotian Shelf Stock 4Vs and 4W (hereafter referred to as 4VsW) (Figure 1). The geographic areas for these two management units are shown in Figure 2. The growth characteristics of the two stock complexes reflect in part the differences in bottom temperatures between areas (Campana et al. 1995). I will summarize the recent history of management of groundfish off Nova Scotia to set the framework for addressing three of the questions posed.

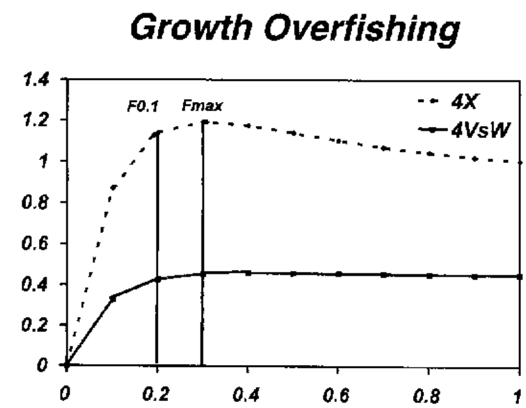


Figure 1. Yield per recruit (kg) as a function of fishing mortality (F) for 4X and 4VsW cod. The annual exploitation rate is $(1-e^{-F})$ where F is the fishing mortality rate. An F of one equals 63% exploitation while an F of 0.2 represents about 18% exploitation.

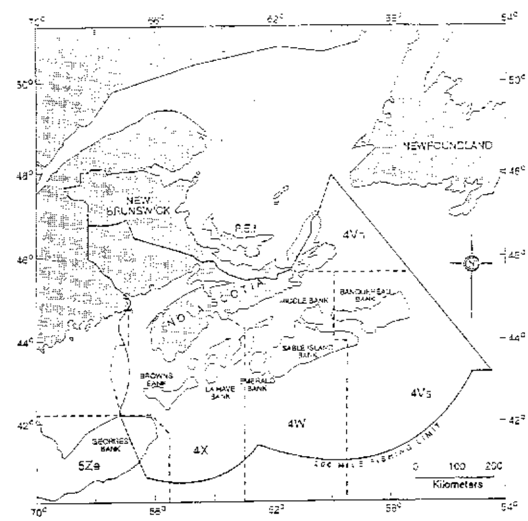


Figure 2. Map of the Atlantic Provinces showing the boundaries of DFO's Scotia-Fundy Region (solid polygon), and NAFO Statistical Areas for which this Region is responsible (4V, 4W, 4X and 5Ze).

Scotian Shelf/Gulf of Maine Groundfish Case History

Two workshops (December, 1993 and October, 1995) were held to evaluate Canadian groundfish management in the Scotian Shelf/Gulf of Maine area. The first workshop (Angel et al. 1994) focused on the degree to which the management objectives had been achieved between 1977 and 1992, and the causes of any shortfalls. The second workshop (Burke et al. 1996) took into account changes in the implementation of groundfish management between 1993 and 1995, and evaluated the need for further modifications. The

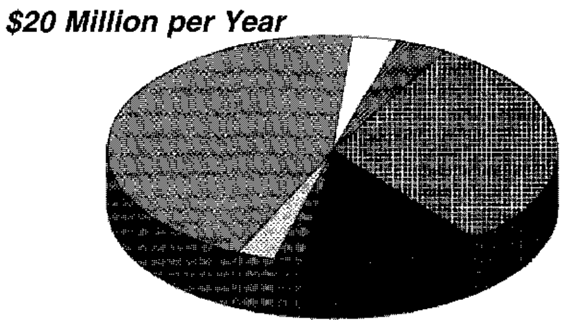


Figure 3. The annual costs of management by the DFO (Department of Fisheries and Oceans Canada) for groundfish in the 4VWX and 5 area during the early 1990s.

latter workshop involved representatives of the fishing industry, as well as fisheries managers, sociologists, economists and scientists.

The Scotian Shelf/Gulf of Maine area (Figure 2) is an interesting study area for several reasons. Canada has tried hard to achieve multiple objectives for the groundfish fishery since the extension of jurisdiction in 1977. The annual costs of groundfish management for this fishing area have been about $20 million (Canadian), with the bulk of the expenditures on enforcement and research (Figure 3). Thus, shortfalls in achieving management objectives have not been due to a lack of financial support or commitment. Trends in the landed value for the overall Canadian fishery of the Maritimes are shown in Figure 4. Although recent years have been relatively high overall, the landed values of groundfish have been declining. It is this component of the fishing industry and management that is addressed. Two cod management units with different ecosystem characteristics are described. Under a similar management regime the cod stock on the eastern Scotian Shelf (4VsW) has collapsed, whereas that in the Gulf of Maine area (4X) is in reasonable shape (Sinclair et al. 1997).

The spawning stock biomass for 4VsW cod is at historically low levels (less than 50,000 tonnes compared to over 200,000 tonnes in 1985). Recruitment has been poor since 1983. In contrast, the spawning stock biomass for 4X cod is at moderate levels compared to the historical record, and recruitment in recent years is similar to the overall 1958 to 1990 time series. For the eastern stock there has been a loss of the spring spawning component on the Western/Sable Island banks (Frank et al. 1994), and fishers have described a loss of some of the smaller spawning components (Younger et al. 1996). The 4VsW cod stock has been closed to fishing since September 1993, but is showing little sign of rebuilding due to continued poor recruitment.

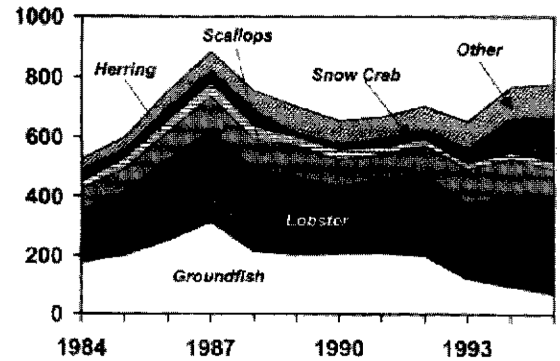


Figure 4. Trends in landed value of the fisheries in the Maritimes Region of Atlantic Canada between 1984 and 1995.

The conservation objectives for the cod stocks since 1977 have been to prevent growth and recruitment overfishing. Growth overfishing occurs when a less than maximal yield is harvested from incoming recruitment, whereas recruitment overfishing occurs when fishing has reduced the capability of the populations to generate average to good year classes. The strategy to achieve the objectives has been to fish at a constant annual level of effort, that needed to meet the $F_{0.1}$ exploitation rate. For cod this rate is about a 20% annual removal of the fishable biomass. The tactic chosen to generate constant effort has been single species quota management. The $F_{0.1}$ strategy, if correctly implemented, prevents growth overfishing (Figure 1). The management plan rules included a caveat with respect to setting quotas, in order to ensure the prevention of recruitment overfishing. The relevant rule (8.1) states that "if the stock assessment provides evidence of levels of spawning stock biomass likely to endanger recruitment, fishing effort in the coming year will be reduced to allow immediate growth in spawning stock biomass".

In spite of the conservative strategy and tactics adopted by Canada with respect to the conservation objectives, the overall management approach involving multiple objectives has proven to be high risk. This is illustrated with reference to the Gordon-Schaefer bioeconomic model (Figure 5). Industry has been encour-

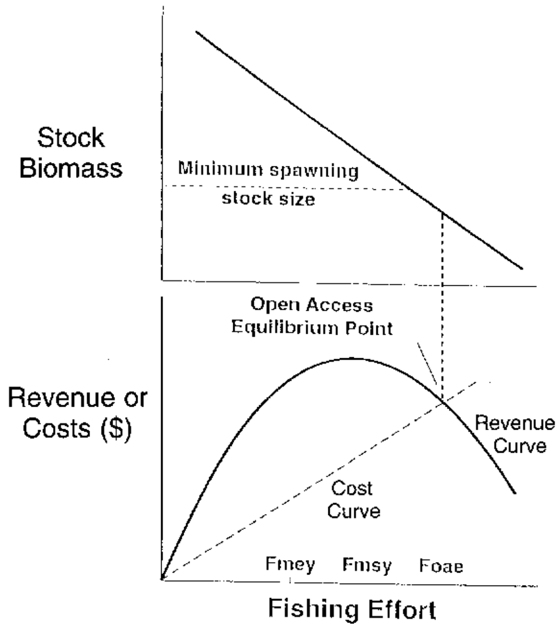


Figure 5. The relationship between minimum spawning stock size (MSB), fishing effort and the open access equilibrium point is illustrated using the Gordon (1954) and Schaeffer (1954) bio-economic model. In the lower part of the figure the dotted straight line is the cost curve whereas the solid curved line is the revenue curve. Fmey, Fmsy, and Foae are fishing effort levels that generate respectively, the maximum economic yeild, the maximum sustainable yield and the open access equilibrium cost (i.e. as net value).

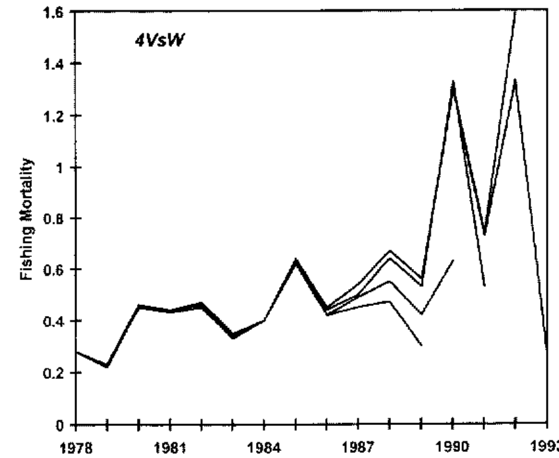


Figure 6a. Trends in estimates of fishing mortality using the sequential population analysis model (SPA) for 4VsW cod. The underestimates of fishing mortality illustrate the so-called retrospective problem for these two management units.

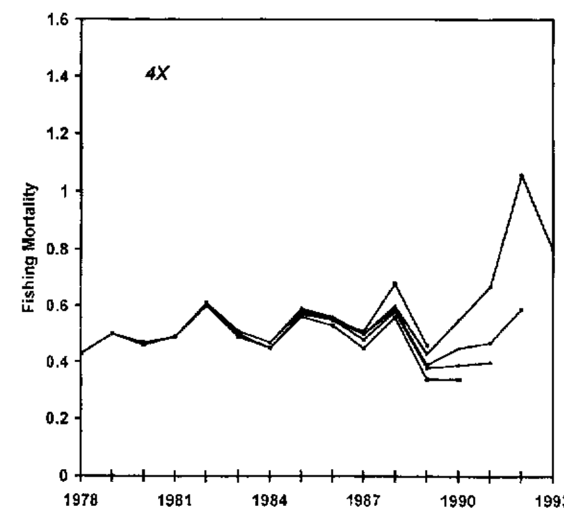


Figure 6b. Trends in estimates of fishing mortality using the sequential population analysis model (SPA) for 4X cod. The underestimates of fishing mortality illustrate the so-called retrospective problem for these two management units.

aged to increase technological efficiency of harvesting, which lowers the cost curve. Furthermore, government subsidization of fishing operations also lowers the cost curve to the participants. These activities result in the open access equilibrium point (OAE) occurring at a higher level of fishing effort than would be the case without increased technological efficiency and subsidization. The high effort levels coincident with OAE may coincide with spawning stock biomass levels below that needed for moderate to good recruitment. If fishing effort is not effectively controlled under the quota management regime, given the ability of industry to break-even at low stock abundance (i.e. due to the lower slope of the cost curve), the fishery is susceptible to collapse. The management approach under multiple objectives is high risk in that conservation targets can only be met if fishing effort is held constant at low levels. Without effective control of effort, given the reduced slope of the cost curve for industry, there is a high probability of long-term collapse. It is in this sense that the management approach is high risk.

The age-structured model used to estimate stock abundance trends and annual fishing mortalities tends to overestimate the former and underestimate the latter for the most recent time period (Mohn 1996a). Each line provides the estimates of fishing mortality over the time period included in the assessment. The earlier values (prior to about 1986) converge whereas the more recent years vary. For example, the estimate of the 1990 fish-

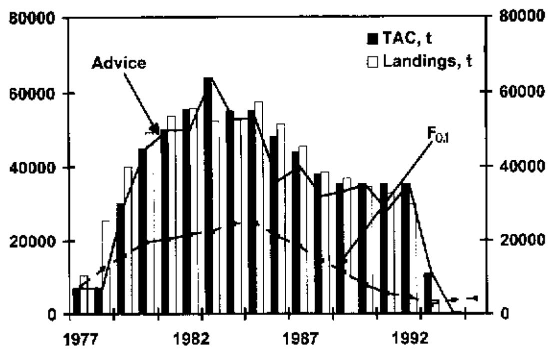


Figure 7. Trends in past scientific advice, present perception of correct $F_{0.1}$ advice, total allowable catches (TACs) set by the Minister of DFO, and reported landings (all in tonnes) for 4VsW cod from 1977 to 1995.

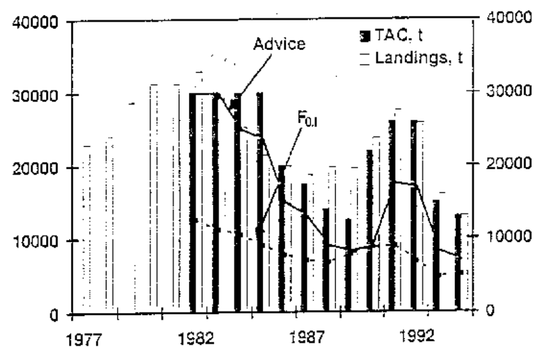


Figure 8. Trends in scientific advice, total allowable catches (TACs) set by the Minister of DFO, and reported landings (all in tonnes) for 4X cod from 1977 to 1995. There were no quotas for this management unit until 1982.

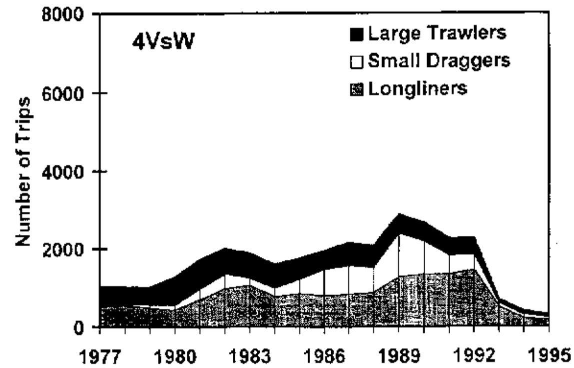


Figure 9a. Trends in numbers of groundfish trips between 1977 and 1995 for large trawlers, small draggers, and longliners in 4VsW.

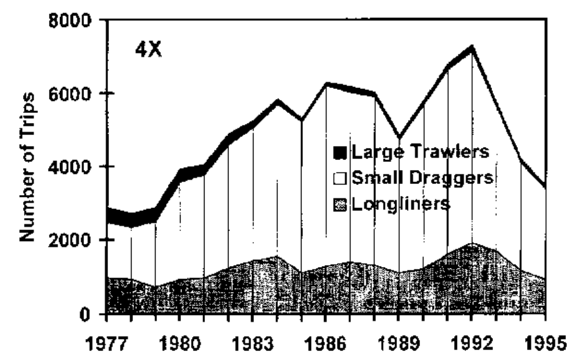


Figure 9b. Trends in numbers of groundfish trips between 1977 and 1995 for large trawlers, small draggers, and longliners in 4X.

ing mortality rate in the 1993 assessment is higher than in that for 1990. This issue has been called the "retrospective problem", and the degree of underestimation of fishing mortality for 4VsW and 4X cod is shown in Figure 6a, b. The problem is particularly severe in 4VsW.

Angel et al. (1994) described a combination of factors that led to inadequate implementation of the chosen tactic of single species quota management. The problems are illustrated by a comparison of the scientific advice, the total allowable catch (TAC) set by the Minister and the reported landings (Figures 7 and 8). There are four points. First, the scientific advice (which was not always at the $F_{0.1}$ level) was sometimes considerably higher than the $F_{0.1}$ level given our present perception of stock biomass trends. Second, the TACs set by the several Ministers of Fisheries and Oceans were often higher than the scientific advice, particularly during periods when the stock was declining. Third, the reported landings were frequently higher than the TAC. This occurred when fisheries that were closed were allowed to continue on a trip limit, or bycatch, when other groundfish quotas were still available. Finally, the reported landings during some years have been less than the TAC. During these years the quotas were essentially unlimiting to fishing effort.

The tactic of single species quota management did not achieve the strategy of constant effort at a low level (Figure 9a, b). In 4VsW the numbers of fishing trips per year rose steadily from 1977 to the late 1980s. The cod fishery in 4VsW may have been near the open access equilibrium point by the late 1980s.

In a 1992 letter from Theophile Samson from Petit de Grat, Isle Madame, Cape Breton he states:

"Having fished inshore in the late 1970s and early 1980s and having a hard time to make a living with the boat I had, I decided with a bigger boat that I would be able to venture up to 25 miles from shore, so in 1983 I got a new 32 foot fibreglass boat which I kept till 1987. Because of the decline of fish within 25 to 30 miles from shore in 1989 I went from a 32 foot to a 42 foot fibreglass longliner which would enable me to venture to greater distances, that is up to 150 miles offshore. Since 1988 we have seen our catches dwindle drastically to a point where it is not economically feasible to fish anymore....

At the Isle Madame Fishermen wharf in Petit de Grat there were 12 longliners, 40 to 45 feet long. Today, 1992 there are but 2 left."

The aggregate number of trips per year in 4X continued to increase until 1993. Effort has declined substantially during the past several years due to stricter implementation of quotas in 4X and the closure in 4VsW.

The trends in exploitation rate for 4VsW and 4X cod (Figure 10) parallel those of fishing effort (Figure 9a, b). The $F_{0.1}$ target implied by the strategy to achieve the conservation objective is about 20%. Exploitation rates rose gradually from 1977 to 1988 for both cod stocks, and then sharply during the early 1990s. For 4X cod the sharp increase in exploitation rate is consistent with the increases in days fishing. However, the estimated increases in 4VsW exploitation rate occurred when effort was relatively stable. Thus, either there was a change in catchability (i.e. fishing mortality per days fishing increased) or an increase in natural mortality. For both management units, due to the shortfalls in management, there has been growth overfishing since about the mid 1980s. Overall exploitation rates were higher in 4X than in 4VsW, yet the fishery on this cod stock within the Gulf of Maine area has survived whilst that on the eastern Scotian Shelf has collapsed. It is difficult to account for the different responses due to fishing practices and shortfalls in management alone. It is to be noted, however, that there are two fisheries-related differences between the management units. There has been a spawning area closure on Browns Bank for haddock in 4X since 1972. This closure may have coincidentally provided some protection for cod which also spawn on the bank during the period of the closure. Second, the large vessel fleet (>100 feet in length) was the dominant gear sector in 4VsW (from a fishing mortality perspective). This fleet has only had a small quota allocation in the Gulf of Maine area.

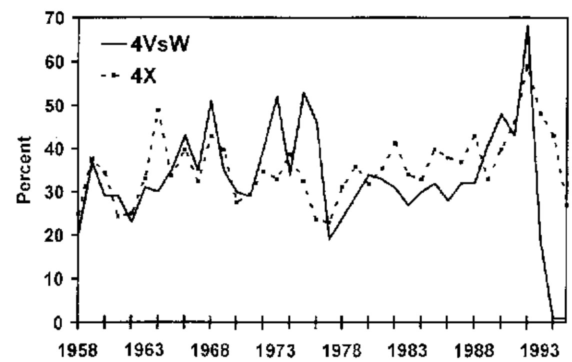


Figure 10. Trends in estimates of exploitation rate (%) for 4VsW and 4X cod between 1958 and 1994. The $F_{0.1}$ target for these two management units is about 20%.

In addition to the above differences in fishing practices that may have contributed to the differential response to fishing effort, there are important ecosystem differences between the Gulf of Maine area and the shelf seas to the east of Halifax towards Labrador. There are strong latitudinal gradients in both surface and bottom temperature (Drinkwater 1996, Drinkwater et al. 1996, Petrie and Drinkwater 1993). To the east of Halifax the summer bottom temperatures are generally less than 4°C, and in recent years (1990s) there has been an increase in the bottom area characterized by below 2°C conditions. For example 40 % of 4VsW has been below 2°C during the 1990 to 1994 period, compared to 14% during the 1975 to 1989 period. Cod tend to move out of water colder than 2°C in this area (Kees Zwanenburg, personal communication). The aggregation of cod into a more limited distributional area during the 1990s in 4VsW may have resulted in an increase in catchability (i.e. higher fishing mortalities per days fishing). Within the Gulf of Maine area not a large part is characterized by summer bottom water temperatures below 2°C (14% in 1990/94 compared to 2% in 1970/74). Thus, one would not expect much of a reduction in the area of cod habitat during the 1977 to 1995 period in the Gulf of Maine area. The extremely low bottom temperatures (i.e. below 2°C) may be unique to this part of the range of Atlantic cod (eastern Scotian Shelf to west Greenland). The cod populations off Iceland, the Faroes, and the European Continental Shelf are predominantly distributed in bottom temperatures above 4°C (Brander 1994). The differences in resilience to high levels of fishing between cod populations off of much of Atlantic Canada compared to those off Europe and in the Gulf of Maine area may be at least partially due to the temperature differences.

Another difference between the cod ecosystem to the east of Halifax compared to that of the Gulf of Maine area is the abundance of seals. If the coastal tag returns for grey seals are representative of the offshore distribution, grey seals are about four times as abundant in 4VsW as they are in 4X (Stobo et al. 1990). In the Gulf of St. Lawrence and off Newfoundland/Labrador there are also harp and hooded seals. The potential for predation on cod in the Gulf of Maine area by pinnipeds is thought to be much less than in the cod habitat to the east of Halifax.

Grey seals have been increasing in abundance at an exponential rate (about 12% a year for the Sable Island population and 9% a year for the Gulf of St. Lawrence population, Mohn and Bowen 1996). Analysis of grey seal diets since 1988 have shown that between 5 to 15%, by weight, of the grey seal diet is juvenile cod (predominantly ages 1 to 3) (Mohn and Bowen 1996). Depending on the assumptions used in their feeding model, Mohn and Bowen (1996) estimate that natural mortality of juvenile cod in 4VsW has increased during the late 1980s and 1990s to as high as 35 % (average age 1 to 3 natural mortality due to seals for the 1989 to 1993 time period). There is considerable controversy over the interpretation of the model results, due primarily to uncertainty in the assumptions concerning other sources of natural mortality of juvenile cod. Irrespective of these uncertainties it is well estimated that grey seals have been consuming more cod by numbers in 4VsW than are caught by the fishery since the mid 1980s, and that this consumption has been increasing with time.

Present Management Approach

New Understanding

From the above case history we have learned that there are important differences in the resilience of populations of the same species to fishing mortality. For example, there has been "sustainable overfishing" of cod in the Gulf of Maine area at very high levels of fishing effort, whereas similar levels of exploitation on the eastern Scotian Shelf, Gulf of St. Lawrence and off Newfoundland/Labrador have contributed to long-term fisheries collapses. The geographic pattern of cod collapses in the North Atlantic suggest that ecosystem differences have compounded the effects of overfishing. The comparative analysis supports the interpretation that increases in the proportion of cod habitat characterized by temperatures below 2°C, and increases in juvenile mortality of cod by seals, may have both contributed to fisheries collapses and will influence the time period of recovery.

Secondly, spatial complexity in population features and of fishing effort may be critically important to sustainability. Most single species management units comprise a complex of spawning components. Quota management for such units does not in itself ensure that the individual components are sustained. There is empirical evidence that spawning components in 4VsW were lost in the mid 1980s due to the concentration of trawling on the spawning areas in the spring. From 1981 to 1985 there was considerable fishing effort in the spring on the cod spawning areas identified by egg and larval surveys. In 1986 the spring effort shifted off the cod spawning banks to the shelf/slope edge in 4Vs. From egg and larval surveys we know that the Sable/Western Bank spring spawning component was lost between 1980 and 1992 (Frank et al. 1994). The patterns in fishing effort support the interpretation that trawling on spawning concentrations between 1981 and 1985 contributed to the loss of reproductive capacity for 4VsW cod. This interpretation is supported by interviews with fishers (Younger et al. 1996).

Using a modeling approach Mohn (1996b) has evaluated the degree to which spawning components within a management unit are susceptible to selective over fishing under $F_{0.1}$ quota management. He also simulated the impact of a spawning closure on biomass trends. The results infer, for management units with a complex of spawning components, some components can be reduced to low levels even though the overall quota is set at the $F_{0.1}$ level.

The importance of spatial structure within management units is also illustrated for Georges Bank haddock. The United States management unit is North Atlantic Fisheries Organization (NAFO) Divisions 5Z and 6. The Marine Resource Monitoring, Assessment and Prediction (MARMAP) data set of NOAA egg and larval surveys indicate that there are two spawning areas within the management unit, one on the northeast peak

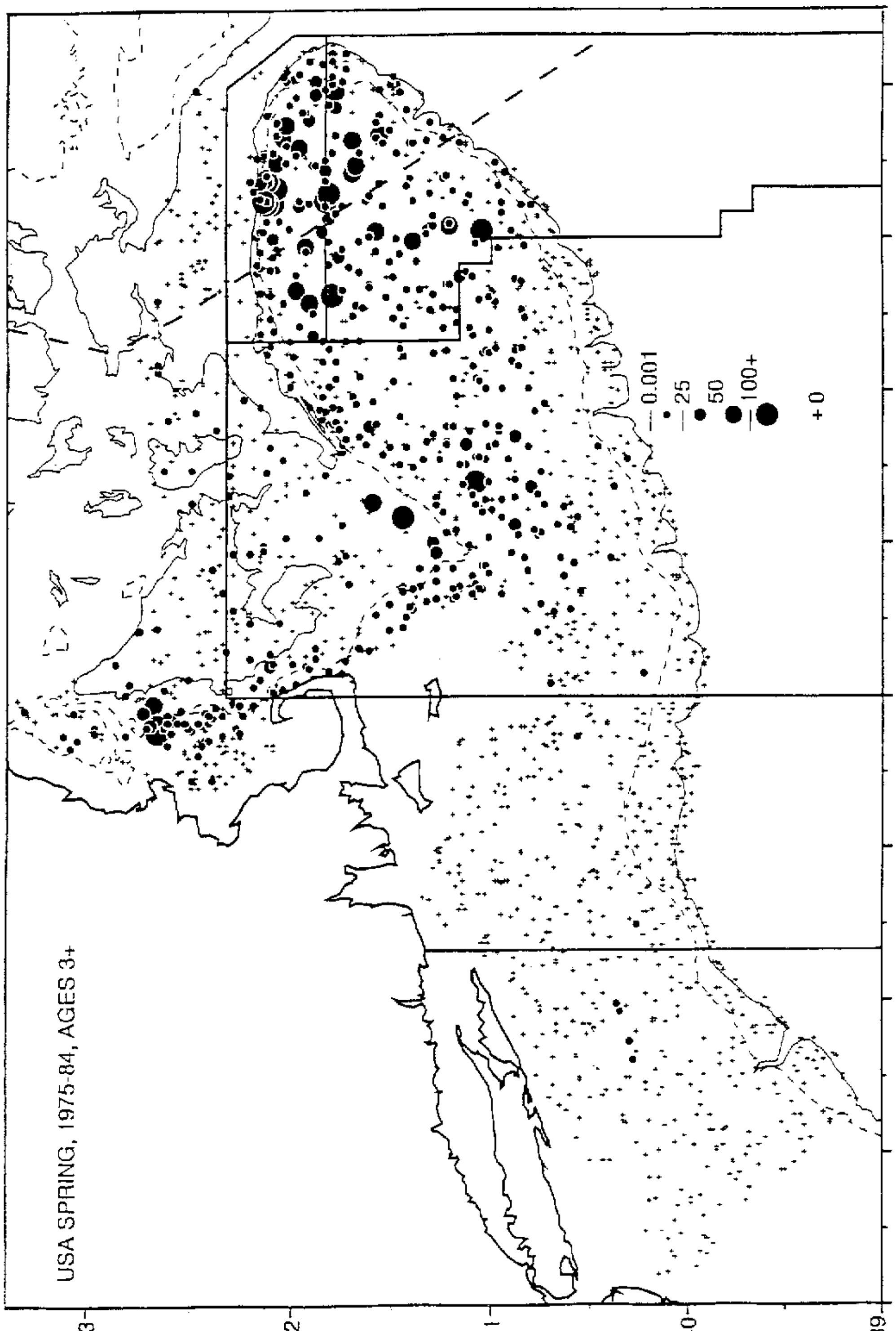


Figure 11a. Distribution of haddock (catch/tow) as observed during the USA spring groundfish trawl survey for the period 1975-1984.

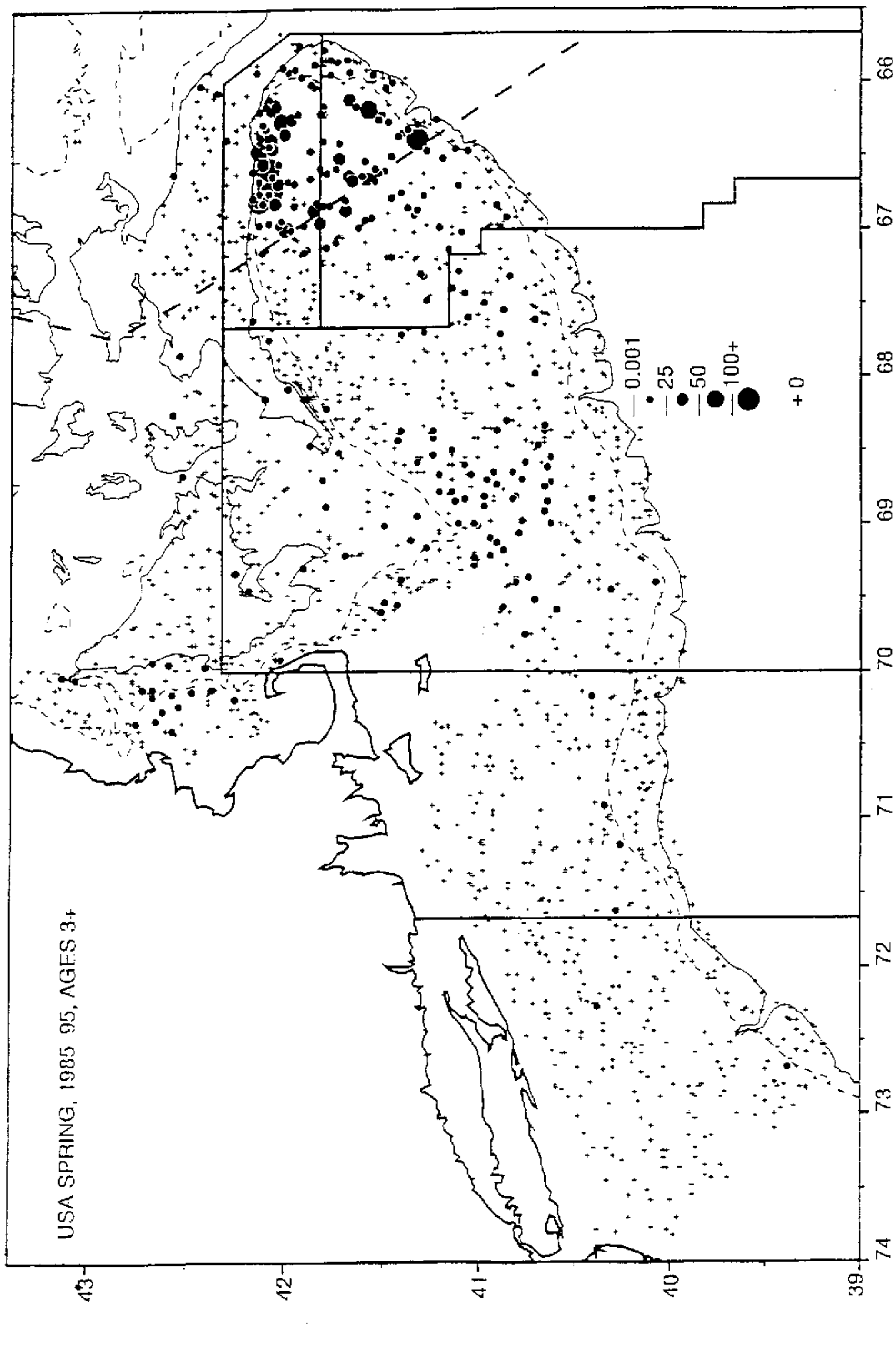


Figure 11b. Distribution of haddock (catch/tow) as observed during the USA spring groundfish trawl survey for the period 1985-1995.

of Georges Bank and the second in the Great South Channel. From a comparison of the research trawl survey haddock distributions in the 1970s and 1990s (Figure 11a, b) it is apparent that the Great South Channel catch/tow is presently at very low levels, while the population spawning on eastern Georges Bank is at moderate levels (Van Eeckhaute et al., in preparation). Recruitment overfishing for the larger United States management unit (5Z and 6) appears to be largely due to loss of geographic spawning potential.

A final example of the importance of spatial structure in fish population dynamics is provided by the recent recovery of the Georges Bank herring population complex. The herring stock in the 5Z and 6 management unit collapsed in the early 1970s (Anthony and Waring 1980). Larval surveys prior to the collapse identified two spawning components (the northeast peak and Nantucket Shoals). During the collapse both spawning components were lost. United States and Canadian larval surveys have described the gradual recovery of herring on Georges Bank in the 1990s. The spatial pattern of spawning at present is very similar to that described before the collapse (Melvin et al., 1995). This suggests that population patterns are defined by relatively persistent circulation features. Within the 4WX herring management unit (see Figure 2 for the geographic area of this management unit) there are also a number of spawning components. Under quota management between 1977 and 1994 several spawning components have been reduced to very low levels (Stephenson et al. 1996). During the past two years special measures are being taken by industry and management to protect the remaining components within a quota management regime.

Thirdly, the recent experiences of groundfish management in 4X (i.e. 1993 to 1995) suggest that quota management can achieve the conservation objectives if implemented appropriately. In Figures 9a, b and 10 it was pointed out that fishing effort and exploitation rate for 4X cod has been reduced significantly since 1993. The exploitation levels are presently close to the $F_{0.1}$ target. Similar trends have been observed for 4X haddock, Scotia-Fundy pollock, and eastern Georges Bank haddock and cod. Two categories of activities have contributed to this turnaround in the performance of single species quota management.

The introduction of individual transferable quotas (ITQs) for the small dragger fleet (vessels less than 65 feet) has resulted in a reduction in fishing capacity for the dominant (with respect to exploitation rate) fleet sector in these management areas. The large draggers (>100 feet) have been on an enterprise allocation scheme since the early 1980s, and capacity reduction has been ongoing since that time (Gardner 1988). In addition, for the fixed gear sectors under competitive quotas (longlines, handlines, gillnets), attempts are being made to reduce capacity through changes in the licensing policy, buybacks and the use of community quotas.

The second category of activities has been changes in the methods of controlling fishing effort. A combination of stiffer administrative sanctions, independent dockside monitoring at a limited number of harbors (paid for by industry) the closure of fishing for all groundfish species to those under competitive quotas when the seasonal quota for a single species is reached, and the use of time/area closures when there is a large by-catch of small fish has resulted in stricter implementation of quota management and improved compliance by fishers (Creed 1996). Also, the use of variable sized square mesh nets by the large trawlers and small draggers has improved the ability of these gear sectors to target certain groundfish species with minimal by-catch and discarding.

The recommendations of the Industry/Department of Fisheries and Oceans Steering Committee of the Second Groundfish Management Workshop for the Scotia-Fundy area define additional changes to enhance the capability of a single species quota management system to achieve the conservation objectives (Burke et al. 1996). They include real-time monitoring of fishing effort in relation to targets estimated from quotas for gear sectors, enterprises and boats. Discrepancies between accumulated days-at-sea and reported landings should allow the identification of misreporting, or problems with the overall total allowable catch. In addition, enhanced use of spawning area closures was recommended in order to protect individual spawning components. In summary, a package of tools should be used to control effort rather than reliance on quota alone.

Fourthly, an important recent contribution to improved fisheries science is our understanding of the causes of the retrospective problems (Figure 6a, b) and methods of correction (Mohn 1996a). A simulation model was used to evaluate the impacts of changes in

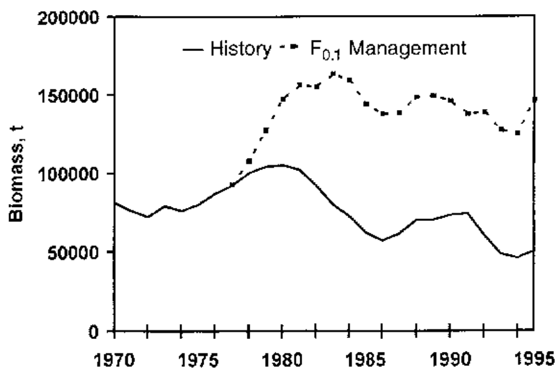


Figure 12. Impacts of fishing beyond the $F_{0.1}$ target on 4X cod biomass. The lower line illustrates the estimates of stock biomass (age 1+) at historical levels of exploitation (see Figure 10). The upper line is the estimate of stock biomass that would have occurred if fishing had been restricted at $F_{0.1}$.

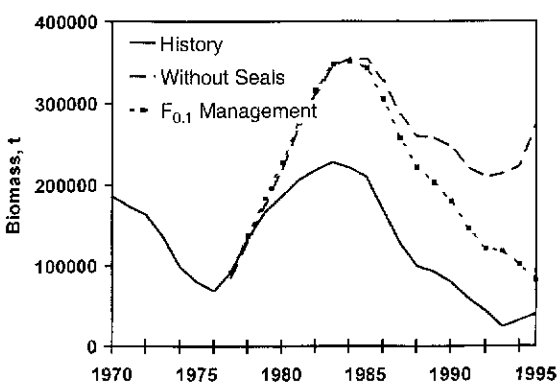


Figure 13. Impacts of fishing beyond the $F_{0.1}$ target and of seal predation on 4VsW cod stock biomass (age 3+). The lower line illustrates the estimates of stock biomass at historical levels of exploitation (see Figure 10). The upper lines show trends in stock biomass with fishing at the $F_{0.1}$ level with and without seal predation on cod juveniles (using model results from Mohn and Bowen. 1996).

natural mortality, discarding, survey time series discontinuities, and survey "year affects" on the accuracy of estimates of exploitation rate and stock biomass. In addition approaches for diagnosis of the existence and causes of the retrospective problems are described. This new understanding of problems with input data for single species quota management should lead to improved accuracy of scientific advice on stock status and recent exploitation rates.

Fifthly, if we achieve improved accuracy of scientific advice on stock status, and the recent successes in implementation of quota management are continued, the $F_{0.1}$ strategy adopted by Canada should go a long way towards achieving the objectives of fisheries management for the Gulf of Maine area. The caveat is that the full geographic spawning potential has to be protected. For example, the stock trends that would have occurred for 4X cod, given observed recruitment, if the $F_{0.1}$ strategy had been implemented, are shown in Figure 12. The stock biomass would have stabilized at a level of about 150,000 tonnes under the $F_{0.1}$ strategy. The difference between the curves represents the shortfalls in the implementation of quota management. In contrast stock size in 4VsW would have declined even under $F_{0.1}$ management given the very poor recruitment since the mid 1980s.

Uncertainties

A key uncertainty in fisheries science is the relative roles of overfishing and ecosystem change on recruitment collapse of diverse management units. There has been growth over fishing for essentially all of the major species harvested in the Gulf of Maine area for several decades. However, only some stocks have collapsed. What are the characteristics of those fisheries that are sustainable at high levels of fishing effort, such as American lobster and some of the tropical tuna species (Fonteneau 1997) It was suggested (Sinclair 1997b) at the Second World Fisheries Congress (Brisbane, 1996) that such management units either have a natural refuge to fishing under present economic constraints (i.e. tropical tunas) and/or are characterized by relatively limited aggregations during the exploited phase of the life history (e.g., American lobsters).

In spite of extensive monitoring and research activity on the Scotian Shelf between 1977 and the present, the causes of the sharp decline in 4VsW cod recruitment since the mid 1980s are still uncertain. For example, a key uncertainty in the estimation of trends in natural mortality due to grey seal predation is the response of other predators of cod to an increase in seal consumption. Little is known about natural mortality of juvenile cod, and food-habits of their predators in this area have not been investigated. Although I have implied above from an analysis of effort patterns over time that the large trawler fleet contributed to the loss of spawning components, less favorable environmental conditions and seal predation probably also play a role in the observed recruitment decline.

The specific issue of uncertainty in understanding the reasons for 4VsW cod recruitment decline leads to the broader issue of lack of scientific consensus within the Gulf of Maine area (and elsewhere) on an operational definition of the minimum spawning stock biomass necessary for moderate to good recruitment. The lack of an acceptable definition impeded the application of rule 8.1 (described above) for the setting of quotas for groundfish off Atlantic Canada. For example, the rule was not applied for 4VsW cod until 1993, by which time the stock had collapsed.

The degree of uncertainty for the 4VsW cod interpretation is illustrated by Figure 13. Biomass trends that would have occurred under $F_{0.1}$ management since 1977, under two recruitment scenarios, are estimated. The lower curve is generated using the recruitment trend from the most recent stock assessments (Fanning et al., 1996). The upper curve uses the high estimate of recruitment trends from the model of Mohn and Bowen (1996), which takes into account grey seal predation on cod juveniles. If the high end estimates of recruitment from the model are realistic, seal predation has played a large role in the stock collapse, and $F_{0.1}$ management would not have prevented major stock decline. However, if the fishery has been the major cause of recruitment decline, management actions in the mid 1980s to reduce fishing effort would have prevented the collapse. The uncertainty in interpretation is a major constraint to future management actions.

Finally, for collapsed stocks there is little understanding of the time scale of recovery. The Arcto-Norwegian cod stock recovered very rapidly, but there is little evidence of strong recruitment to the collapsed cod stocks to the east of Halifax. From herring examples the recovery period can be very long (two decades for Georges Bank and Magdellan Islands herring, and Dogger Bank herring (North Sea) which collapsed in the 1950s has not yet recovered).

Role of Scientific Advice in Collapses

The overly optimistic scientific advice during the 1977 to 1993 period was a contributing factor in the cod collapse (see Walters and Maguire (1996) for a detailed review). Angel et al. (1994) and Burke et al. (1996) however, conclude that for the Scotia-Fundy area (i.e. Gulf of Maine area and the Scotian Shelf) shortfalls in attaining conservation objectives of management were due to deficiencies in the overall management system (from strategic planning and resource advice to monitoring and enforcement). They identify several key problems with the scientific advice, most of which have been mentioned above. They are:

1. A false sense of resilience of cod stocks, based on North Sea and other European continental shelf gadoid stocks which have proven to be sustainable at high levels of exploitation,
2. The systematic underestimation of exploitation rate and overestimation of biomass due to the retrospective problem with the virtual population analysis model tuning procedure,
3. Lack of consensus on an operational definition of minimum spawning stock biomass which prevented the early application of rule 8.1,
4. Lack of real-time monitoring of fishing effort (which in retrospect provided a clear signal that the implementation of quota management was not resulting in a constant level of annual effort),
5. Overall slow response to danger signals, and thus the precautionary approach was not used.

Basic Concepts Underlying Fisheries Management

When we talk about ecosystem management for marine fisheries it is perhaps implied that fishing targets for diverse commercially important species will be adjusted taking into consideration food and predator fluctuations (i.e. the herring landings could be kept particularly low if it were expected that cod abundance is regulated by the amount of herring feed). Ecosystem management in the above sense is important to the degree that abundance is regulated by food-chain interactions in an "abundance dependent" manner.

There are empirical observations for shelf sea ecosystems that the communities are relatively uncoupled, and that the component populations are not regulated by "abundance dependent" food chain interactions. The nature of the ecosystem interactions will determine the degree to which ecosystem considerations need to be taken into account in fisheries management. I will present a case that for shelf sea fisheries in north temperature ecosystems, such as the Gulf of Maine area, that the uncoupled nature of the food-chains and communities infers that the benefits of management can be achieved with a predominantly single species approach. An ecosystem context is important for management decisions on a resource by resource basis, but ecosystem management itself may not be required.

For some ecosystems there is evidence of tight coupling and "abundance dependent" population regula-

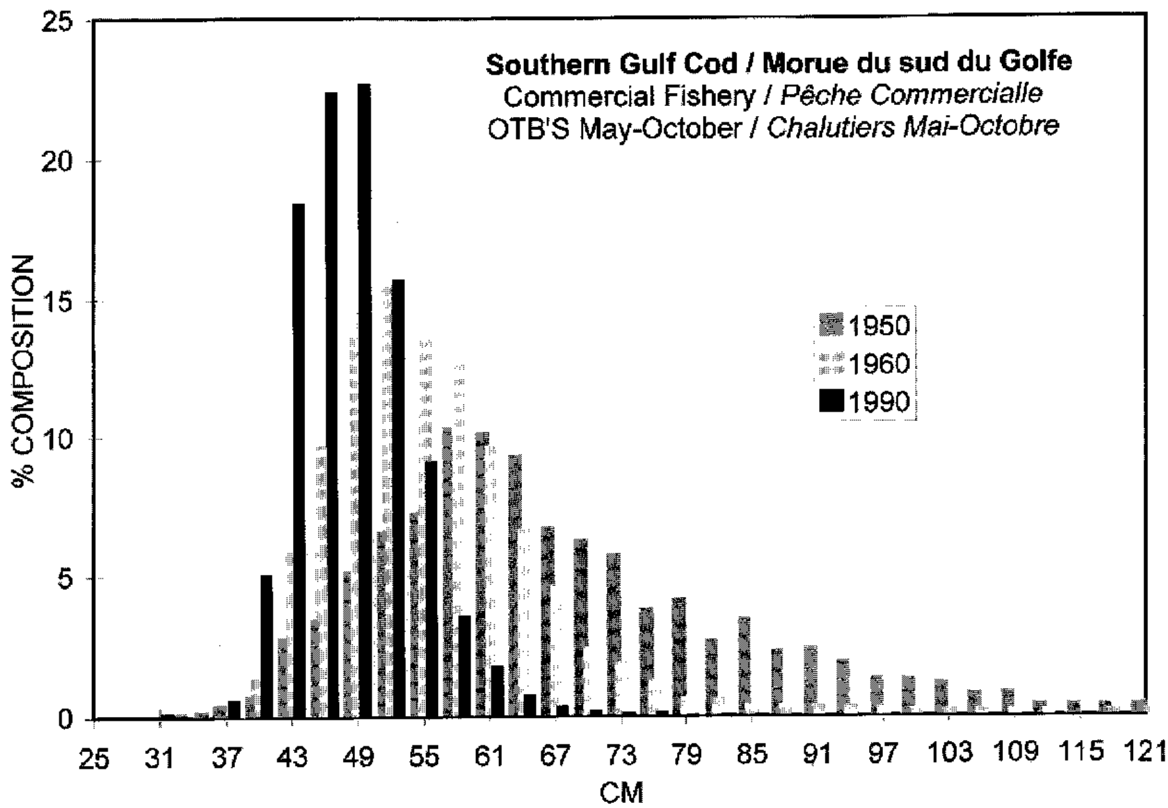


Figure 14. Length frequencies of cod in the Gulf of St. Lawrence fishery in 1950, 1960, and 1990.

tions of component species. Paine (1980) summarizes the empirical observations and theory on the role of key predators within rocky intertidal communities. Removal of certain predators can lead to changes in community structure. For temperate lakes there is also evidence that removal of large predators can have important food web effects. This process has been defined as the "trophic cascade" and is described in detail by Carpenter and Kitchell (1993). For north temperate shelf seas, however, there is little empirical evidence that heavy fishing has influenced community structure or is leading to a loss of biodiversity other than by the direct effect of depletion of target species.

In contrast to the experience in lakes, removal of larger fish in shelf sea communities has not led to change in the rank order of zooplankton species. To illustrate this point, in perhaps an overly simplistic manner, I have looked at the changes in length composition of the summer groundfish landings in the Gulf of St. Lawrence prior to and after changes in fishing intensity in the early 1960s (Figure 14). As expected

Table 2.
Estimates of zooplankton abundance on the Scotian Shelf during July 1963 and 1993 using Continuous Plankton Recorder data (numbers/sample).

Species	1963	Rank	1993	Rank
Temora longicornus	562	1	330	1
Pseudocalonus elongatus	358	2	116	2
Evadne spp.	227	3	31	8
Oithona spp.	152	4	52	6
Calanus i-iv	139	5	54	5
Centropages hamatus	49	6	111	3
Chaetognatha	44	7	41	7
Calanus finmarchicus	25	8	7	10
Centropages typicus	13	9	93	4
Limacina retroversa	13	10	8	9
Tortanus discaudatus	10	11	0	12
Metridia lucerns	4	12	2	11

the larger fish are no longer available. Similar changes occurred on the Scotian Shelf and Gulf of Maine area but the data are not as easily available. The rank order in zooplankton species composition and abundance prior to and after the changes in fishing capacity is illustrated in Table 2. There is little evidence of a change in species or size composition. Koslow (1983) in a detailed analysis of the North Sea ecosystem concluded that the shelf ecosystem did not respond to predator removal in a manner consistent with the trophic cascade hypothesis.

Mahon et al. (personal communication) have used the aggregate groundfish trawl survey data to describe fish community structure from Cape Hatteras to Cape Chidley (top of Labrador). Several methods were used to evaluate associations. The statistical methods led to the conclusion that there are weak associations between the distributions of demersal species over this biogeographical scale. Secondly, the analysis did not find that there have been changes in community structure over the 1975 to 1994 time period. Individual species have changed their distributional range in response to shifts in temperature conditions (e.g., Arctic cod and capelin are distributed more to the southwest in the 1990s compared to the 1975 to 1989 period). A general conclusion that emerges from the analysis is that species are responding independently to environmental variability, but that the fish community assemblages (weak as they are) are persistent.

The above conclusions for the northwest Atlantic are consistent with the recent results of a study of groundfish assemblage structure in the northwestern North Sea (Greenstreet and Hall 1996). The 1929 to 1953 period is compared to the 1980 to 1993 period. I quote in full two conclusions from the summary:

> "4. Examination of species aggregated length-frequency distributions suggested that by the 1980s there had been a shift towards assemblages in which smaller fish were more highly represented. This was only apparent, however, in the whole groundfish assemblage; the length-frequency distributions of non-targeted species were almost identical in the two time periods.
>
> 5. Overall, the results suggest that, although differences in the structure of the whole fish assemblage can be detected, the non-target groundfish assemblage appears to have remained relatively unchanged, despite a century of intensive fishing activity."

For the Gulf of Maine area it has been reported that removal of gadoids and flatfish on Georges Bank has led to a shift in community structure dominated by skates, and that sand lance had replaced herring (Sherman et al. 1981). The longer term and broader scale analysis summarized above does not support the conclusion that there have been shifts in community structure (Mahon et al. personal communication). Skates have not increased in abundance on the Scotian Shelf in response to a decline in gadoid abundances, and both sandlance and herring can be abundant at the same time (which is presently the case for the Scotian Shelf). An alternate interpretation of the skate/sandlance fluctuations on Georges Bank is that these populations were responding independently to environmental variability, rather than increasing due to a food-chain event caused by over fishing of competitors.

In summary, there is considerable empirical evidence for north temperate shelf sea, such as the Gulf of Maine area, that the food-chains are relatively uncoupled. Other ecosystems which have been studied in some detail also suggest weak community associations. For example the FAUNMAP Working Group (FAUNMAP 1996) have described the spatial response of mammals in the United States to environmental fluctuations during the late Quaternary [the time period of the analysis was Full Glacial (15,000 to 20,000 years ago), Late Glacial (10,000 to 15,000 years ago), and Late Holocene (500 to 4000 years ago)]. They conclude that species responded independently to environmental variability, and that community structures are ephemeral. In their words (p. 1605):

> "Models for future change must rely increasingly on individual species and their requirements, rather than species associations."

Although counter-initiative, it may well be that within some ecosystems food-chain associations do not control the temporal fluctuations in abundance of component populations in an "abundance dependent" manner. This is an old debate in ecology which has not been resolved in a satisfactory manner (Andrewartha and Birch, 1954). Many ecologists assume that intraspecific competition has to occur in order for populations to be limited at their characteristic abundance levels; for example, Hilborn et al. (1995) state (p. 48):

> "Competition for resources **must** occur for most animal populations, but in the study of exploited fish populations, the relationship between population size and reproductive surplus has been the subject of much controversy (emphasis added)."

I have argued that for species with complex life histories "abundance-dependent" vagrancy could be sufficient for the regulation of population abundance if food-chain interactions are not themselves observed to act in this manner (Sinclair 1988, Sinclair and Iles 1989).

In summary, there are a range of empirical observations on fluctuation in abundance of diverse species in the Gulf of Maine area that support the interpretation of a loosely coupled community. From a trophic dynamic perspective it has also been suggested that trophic level coupling is anomalous for Georges Bank (see discussion in Sinclair et al. 1992). There are theoretical reasons why populations of marine species with complex life histories may be controlled directly by physical oceanographic processes without "abundance dependent" food-chain regulation. From this perspective I would argue that we may be fortunate that full-fledged ecosystem management may not be necessary, fortunately, because the knowledge and data requirements for such an approach are well beyond that presently available.

Ecosystem Approach

In the initial part of this paper I concluded that ecosystem differences between the eastern Scotian Shelf and the Gulf of Maine area (including temperature conditions and predation by grey seals on juvenile cod) have contributed to the differential responses of two cod population complexes to comparable levels of fishing pressure. Above I have argued that, due to the relatively uncoupled nature of the Gulf of Maine area ecosystem, management may not be necessary. This may sound contradictory, and thus needs clarification. The present single species management approach implies that there are no trends in natural mortality of a target species due to changes in abundance of other commercially harvested species that are prey or predators. In the cod case history summarized here, it is concluded that natural mortality of juvenile cod on the eastern Scotian Shelf has a temporal trend due to increases in seal predation. However, this trend is not thought to be due to current single species fisheries management practices. It may be useful to differentiate between the two concepts of "ecosystem management" and "single species management within an ecosystem context."

We are fortunate that Larkin (1996) has very recently reviewed the global literature on "concepts and issues in marine ecosystem management". I will use his review to amplify this distinction between ecosystem management and an ecosystem context. At the end of the section on ecological models for marine ecosystem management, he draws conclusions on both the short-term and long-term perspective (p. 153):

> "The close collaboration of oceanographers, ocean ecologists and fisheries biologists in ecosystem modeling holds promise for long-term understanding but in the short-term is unlikely to inspire substantial changes in management tactics.... Even the long-term relevance of ecosystem understandings to fisheries management may prove to be elusive."

Given the constraint to our understanding of marine ecosystems Larkin is supportive of an alternative approach entitled integrated fisheries management (McGlade 1989). This approach nests an awareness of the ecological basis of fish production within a regulatory framework that focuses on the capability of controlling human activities. Burke et al. (1996) describe a fisheries management model that facilitates the analysis of fisheries. The 32 recommendations for improvement of the groundfish management system in the Gulf of Maine area and on the Scotian Shelf were grouped within eight boxes of the model (strategic planning, annual management planning, business analysis, resource analysis, support services, entitlements, catch/effort monitoring, and enforcement). The approach being taken is consistent with the integrated fisheries management concept. Peter Larkin interprets marine ecosystem management for fisheries, in the short-term at least, to be management of fishing capacity and effort with an "awareness of ecosystem properties". I concur with the flavor of Larkin's prognosis.

Acknowledgments

The reviews by Stratis Gavaris and Ralph Halliday are gratefully acknowledged, as is the contribution by Wanda Farrell to the manuscript preparation. The analysis of zooplankton abundance in the Scotian Shelf was provided by Mary Kennedy.

References

Andrewartha, H.G. and L.C. Birch. 1954. *The distribution and abundance of animals.* Chicago: University of Chicago Press.

Angel, J.R., D.L. Burke, R.N. O'Boyle, F.G. Peacock, M. Sinclair and K.C.T. Zwanenburg. 1994. Report of the workshop on Scotia-Fundy groundfish management from 1977 to 1993. *Can. Tech. Rep. Fish. Aquat. Sci.* 1979: vi + 175 p.

Anthony, V.C. and G. Waring. 1980. The assessment and management of the Georges Bank herring fishery. Rapp. P.-v. Réun. *Cons. int. Explor. Mer* 177: 72-111.

Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. *Fish. Invest. Land.*, Ser. 219.

Brander, K.M. 1994. Patterns of distribution, spawning, and growth in North Atlantic cod: the utility of inter-regional comparisons. *ICES Mar. Sci. Symp.* 198: 406-413.

Burke, D.L, R.N. O'Boyle, P. Partington and M. Sinclair. 1996. Report of the Second Workshop on Scotia-Fundy Groundfish Management. *Can. Tech. Rep. Fish. Aquat. Sci.* 2100: vii + 247 p.

Campana, S.E., R.K. Mohn, S.J. Smith and G.A. Chouinard. 1995. Spatial implications of a temperature-based growth model for Atlantic cod (*Gadus morhua*) off the eastern coast of Canada. *Can. J. Fish. Aquat. Sci.* 52: 2445-2456.

Carpenter, S.R. and J.F. Kitchell. 1993. *The Trophic Cascade in Lakes.* Cambridge: Cambridge University Press. 385 p.

Creed, C. 1996. Social responses to ITQs: cheating and stewardship in the Canadian Scotia-Fundy inshore mobile gear sector; pp. 72-82. In Report of the Second Workshop on Groundfish Management, eds. D.L. Burke et al. *Can. Tech. Rep. Fish. Aquat. Sci.* 2100.

Drinkwater, K.F. 1996. Atmospheric and oceanic variability in the northwest Atlantic during the 1980s and early 1990s. *J. Northw. Atl. Fish. Sci.* 18: 77-97.

Drinkwater, K.F., E. Colburne and D. Gilbert. 1996. Overview of environmental conditions in the northwest Atlantic in 1994. *NAFO Sci. Coun. Studies* 25: 25-58.

Fanning, L.P, R.K. Mohn and W.A. MacEachern. 1996. Assessment of 4VsW cod in 1995 with consideration of ecological indicators on stock status. *DFO Atl. Fish. Res. Doc.* 96/27, 32 p..

FAUNMAP. 1996. Spatial response of mammals to late quaternary environmental fluctuations. *Science* 272: 1601-1606.

Fonteneau, A. 1997. A critical review of tuna stocks and fisheries trends worldwide and why some tuna stocks are not yet overexploited. 1997. Why do some fisheries survive and other collapse. World Fisheries Congress (2nd: 1996. Brisbane, Qld). Developing and Sustaining World Fisheries resources: the state of science and management: In *2nd World Fisheries Congress Proceedings*. eds. D.A. Hancock, A. Grant, D.C. Smith, and J.P. Beumer. 23-35.

Frank, K.T., K.F. Drinkwater, and F.H. Page. 1994. Possible causes of recent trends and fluctuations in Scotian Shelf/Gulf of Maine cod stocks. *ICES Mar. Sci. Symp.* 198: 110-120.

Gardner, M. 1988. Enterprise allocation system in the offshore sector in Atlantic Canada. *Mar. Res. Econ.* 5: 389-414.

Gordon, H. Scott. 1954. The economic theory of a common property: the fishery. *J. Political Econ.* 62: 124-142.

Greenstreet, S.P.R. and S.J. Hall. 1996. Fishing and the groundfish assemblage structure in the north-western North Sea: an analysis of long-term and spatial trends. *J. Animal Ecol.* 65 (in press).

Hilborn, R., C.J. Walters and D. Ludwig. 1995. Sustainable exploitation of renewable resources. *Annual Rev. Ecol. Syst.* 25: 45-67.

Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe. Rapp. P.-v. *Cons. perm. int. Explor. Mer* 20: 1-228.

Koslow, J. A. 1983. Zooplankton community structure in the North Sea and Northeast Atlantic: development and test of a biological model. *Canadian J. Fish. Aquat. Sci.* 40: 1912-1924.

Larkin, P.A. 1996. Concepts and issues in marine ecosystem management. *Reviews in Fish Biology and Fisheries* 6: 139-164.

Mahon, R. et al., (personal communication)

Mayr, E. 1982. *The Growth of Biological Thought.* Cambridge: Harvard University Press.

McGlade, J.M. 1989. Integrated fisheries management models: understanding the limits to marine resource exploitation; pp. 139-165. In *Mathematical Analysis of Fish Stock Dynamics,* eds. E.F. Edwards and B.A. Megrey. Bethesda, MD: Am. Fish. Soc.

Melvin, G., F.J. Fife, J.B. Sochasky, M.J. Power and R.L. Stephenson. 1995. The 1995 update on Georges Bank 5Z herring stock. *DFO Atl. Fish. Res. Doc.* 96/: 50 p.

Mohn, R. 1996a. The respective problem in sequential population analysis: an investigation using cod fishery and simulated data. *ICES Journal of Marine Science,* (submitted)

Mohn, R. 1996b. Assessing closed areas with a fisheries model having several spawning components; pp. 157-169. In Report of the Second Workshop on Groundfish Management, eds. D.L. Burke et al. *Can. Tech. Rep. Fish. Aquat. Sci.* 2100.

Mohn, R. and W.D. Bowen. 1996. Grey seal predation on the eastern Scotian Shelf: modelling the impact on Atlantic cod. *Can. J. Fish. Aquat. Sci.* (in press).

Paine, R.T. 1980. Food webs: linkage interaction strength, and community infrastructure. *J. Anim. Ecol.* 49: 667-685.

Petrie, B. and K. Drinkwater. 1993. Temperature and salinity variability on the Scotian Shelf and in the Gulf of Maine. 1945-1990. *J. Geophys. Res.* 98: 20079-20089.

Schaefer, M.B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Bull. Inter. Amer. Trop. Tuna Comm.* 1: 26-56.

Sherman, K., C. Jones, L. Sullivan, W. Smith, P. Berrien and L. Ejsymont. 1981. Congruent shifts in sand eel abundance in western and eastern North Atlantic ecosystems. *Nature* 291: 486-489.

Sinclair, M. 1988. Marine Populations: an essay on population regulation and specification. University of Washington Press, Seattle: 252 p.

Sinclair, M and T.D. Iles. 1989. Population regulation and operation in the oceans. *J. du Conseil* 45: 165-175.

Sinclair, M., S. Wilson and S. Rao. 1992. Overview of the biological oceanography of the Gulf of Maine; In *Proceedings of the Gulf of Maine Workshop,* eds. J. Wiggin and C.N.K. Mowers. 91-111. Boston: Urban Harbors Institute, University of Massachussets at Boston.

Sinclair, M. 1996a. Recruitment in fish populations: the paradigm shift generated by ICES Committee A in *Early Life History and Recruitment in Fish Population,* [eds.] R.C. Chambers and E.A. Trippel, Chapman and Hall, in press.

Sinclair, M. R. 1997. Issues and outcomes for theme 1. World Fisheries Congress (2nd: 1996. Brisbane, Qld). Developing and Sustaining World Fisheries resources: the state of science and management: In *2nd World Fisheries Congress Proceedings.* eds. D.A. Hancock, A. Grant, D.C. Smith, and J.P. Beumer. 157-166.

Sinclair, M. R., R. O'Boyle, D. L. Burke, and G. Peacock. 1997. Why do some fisheries survive and other collapse. World Fisheries Congress (2nd: 1996. Brisbane, Qld). Developing and Sustaining World Fisheries resources: the state of science and management: In *2nd World Fisheries Congress Proceedings.* eds. D.A. Hancock, A. Grant, D.C. Smith, and J.P. Beumer. 23-35.

Smith, T.D. 1994. *Scaling fisheries: the science of measuring the effects of fishing. 1855-1955.* Cambridge: Cambridge University Press.

Stephenson, R.L., M.J. Power, F.J. Fife, G.D. Melvin, K.J. Clark and S. Gavaris. 1996. Evaluation of the stock status of 4WX herring. *DFO Atl. Fish. Res. Doc.* 96/28.

Stobo, W.T., B. Beck and J.K. Horne. 1990. Seasonal movements of grey seals *(Halichoerus grypus)* in the northwest Atlantic; In Population Biology of Sealworm *(Pseudoterranova decipiens)* in relation to its intermediate and seal hosts. ed. W.D. Bowen, 199-213. *Can. Bull. Fish. Aquat. Sci.* 222.

VanEeckhaute. L., S. Gavaris and E. Trippel (in prep.). Relative abundance and migration of haddock across the Canada/USA boundary.

Walters, C. and J.-J. Maguire. 1996. Lessons for stock assessment from the northern cod collapse. *Reviews in Fish Biology and Fisheries* 6: 125-137.

Younger, A., K. Healey, M. Sinclair and E. Trippel. 1996. Fisheries knowledge of spawning locations on the Scotian Shelf; In *Report of the Second Workshop on Groundfish Management.* eds. D.L. Burke et al. 147-156. *Can. Tech. Rep. Fish. Aquat. Sci.* 2100.

Zwanenburg, Kees. (personal communication)

Goals and Scope of Ecosystem Modeling

Eileen E. Hofmann
Center for Coastal Physical Oceanography, Old Dominion University

Introduction

Recent developments in mathematical modeling of oceanographic processes have opened the possibility of predictive models for coastal marine ecosystems (see Hofmann and Lascara, in press a for a review). Prediction of coastal ecosystem structure and function depends on having an understanding of the physical and biological processes that control the abundance and productivity of coastal organisms. Interest in developing such a capability arises from issues ranging from marine resource management and climate change to those related to human health and safety. These different issues have resulted in prediction of marine ecosystem responses being identified as one of the goals of the Gulf of Maine program. However, the different predictive needs cover a wide range of space and time scales, which makes development of a predictive ecosystem model for the Gulf of Maine, or any other coastal system, difficult.

Predictive ecosystem models are, for the purpose of this paper, defined to be those that are forced with observations to produce a simulated distribution of a property that is then compared with observations from a specific time and/or location. Models that have as their objective reproducing phenomena such as a spring bloom or subsurface chlorophyll maxima are process models and are not predictive in nature. The minimal requirement for a predictive model is that it must reproduce patterns in observations, such as the timing of maxima or minima in concentrations, the relative abundance of organisms, and the gradients in distribution patterns. Also, the simulated distributions must account for some percent of the variance in the observations.

The mathematical models by Riley (1946, 1947) that were constructed to investigate processes controlling seasonal variability in phytoplankton and zooplankton populations on Georges Bank provide the origin for coastal marine ecosystem models. These models were time-dependent and did not include explicit representation of environmental effects. In the 1970s, the first ecosystem models that included circulation explicitly as part of the dynamics were introduced (e.g., Walsh, 1975; Wroblewski, 1977). These models resulted from the development of large multidisciplinary oceanographic programs, which provided concurrent measurements of physical and biological processes. The coupled physical-biological models were used to investigate the processes that control the space and time variability of primary production in upwelling regions. Recently, the coupled biological models have been combined with data assimilation methods (e.g., Lawson et al., 1995; Fasham and Evans, 1995; Matear, 1995; Lawson et al., 1996) to develop data assimilative models. This development, along with advances in circulation models, has made the prediction of coastal marine ecosystems a possibility.

The objective of this paper is to briefly review the current status of predictive models for coastal marine ecosystems and to indicate what directions need to be followed for the development of such models for the Gulf of Maine. The following sections provide a discussion of time and space scales of physical and biological processes in marine systems and of the types of models that have been used to address marine ecosystem questions. This is followed by a brief discussion of the status of ecosystem modeling for coastal marine systems and the status of such models for the Gulf of Maine. The summary section provides some recommendations for developing ecosystem models for the Gulf of Maine.

Space and Time Scales of Physical and Biological Processes

The range of possible space and time scales over which physical and biological oceanographic processes operate covers many orders of magnitude (e.g., Denman and Powell, 1984; Legendre and Demers, 1984; Murphy et al., 1988; Nihoul and Djenidi, 1991). For physical processes, these range from dissipative processes, which operate at short space and time scales, to scales associated with ocean gyres and the global ocean (Figure 1a). In between are the scales that characterize the mesoscale variability of the oceanic environment; however, the wide range of space and time scales associated with physical oceanographic processes are not independent. Rather, these should be regarded as a cascade of scales through which information can be transferred from large to small scales and vice versa.

Similarly, the range of space and time scales over which individual organisms and populations of organisms exist is large (Figure 1b), and these scales overlap with a wide variety of physical scales and, consequently, physical processes. Therefore, modifications that affect circulation dynamics can potentially influence a wide range of biological processes. Moreover, modifications that affect individual biological components have the potential of cascading throughout the marine food web. Thus, seemingly small perturbations at one trophic level can potentially have a large effect on food web components at other trophic levels.

Although the range of possible scales is large, circulation and biological processes have associated with them certain inherent space and time scales. For example, the scales of spatial structures observed for marine plankton distributions can be represented in terms of balances between diffusion, growth (Kierstead and Slobodkin, 1953), and grazing (Wroblewski et al., 1975; Wroblewski and O'Brien, 1976) processes. Other fundamental scales, such as mixed layer (Sverdrup, 1953) or euphotic zone depths, are important in regulating the spatial distribution of plankton populations. Inherent time scales, such as population doubling times, diurnal variations in light, or seasonal changes in nutrient inputs, impart spatial structures to marine ecosystems which produce specific types of structures in marine biological populations. Circulation processes tend to be influenced by length scales, such as the internal Rossby radius of deformation and the geometry of a basin or shelf region. The dominant physical time scales are usually determined by processes, such as tidal forcing, episodic wind and storm mixing of the upper ocean, and seasonal changes in large-scale wind systems, for example.

The largest and smallest space scales that numerical models of circulation and biological processes can resolve are determined by the model domain and grid size, respectively. Processes that operate at scales larger than the model domain are input through the boundary conditions. Those smaller than the model grid are handled through parameterizations that represent subgrid scale processes (e.g., turbulent diffusion). The range of time scales that can be resolved in numerical models is usually determined by the time scale of the process of interest and the time interval used for the numerical integration. Constructing circulation or biological models that can resolve specific ranges of space and time scales is usually not difficult. The difficulty comes when attempting to combine circulation and biological processes in a single model. Often the resolution requirements for each are different and can be contradictory.

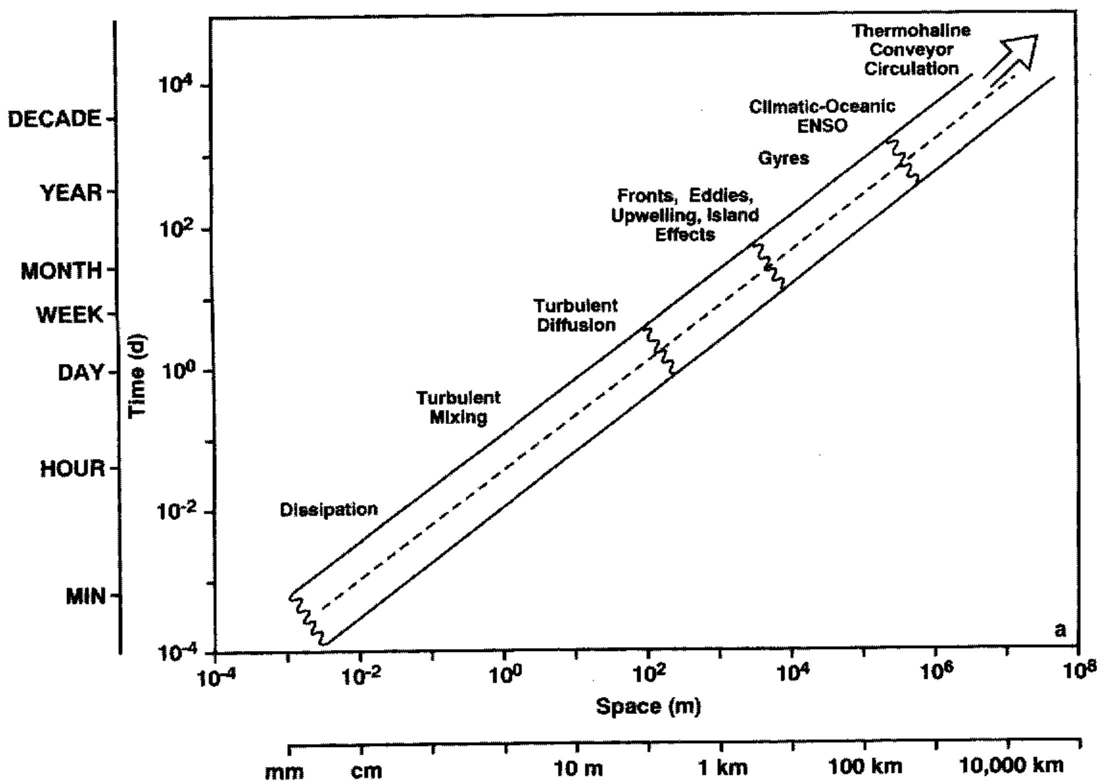
Approaches to Ecosystem Modeling

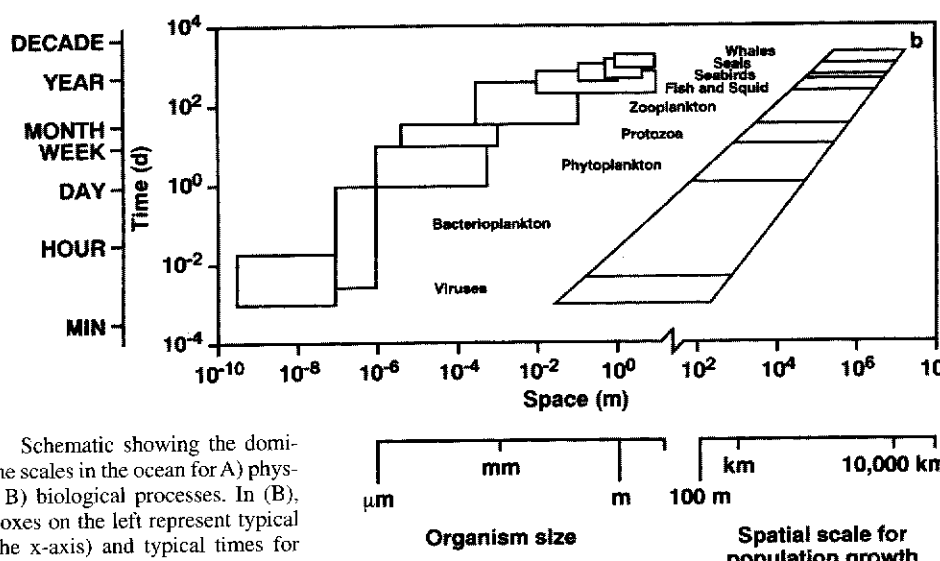
Eulerian Models

An Eulerian model provides a three-dimensional estimate of the distribution of properties at specific locations over time. For non-conservative substances, such as biological properties, the Eulerian equations are of the form:

$$\frac{\partial B}{\partial t} + \nabla \cdot \left(\vec{V}B\right) - \nabla \cdot (K \cdot \nabla B) = \textit{Biological Sources/Sinks.} \quad (1)$$

The first term represents the time (t) rate of change of the biological property, B. The next two terms represent the three-dimensional spatial distribution of B that results from the effects of advection and diffusion, respectively. The biological processes that result in the production or loss of B are given by the *Source/Sink* terms. The vector operator denotes changes in the x, y, and z directions. Advective velocities and diffusive rates in the three dimensions are denoted by $\vec{V}$ and K, respectively.





Figures 1a & 1b. Schematic showing the dominant space and time scales in the ocean for A) physical motions and B) biological processes. In (B), the overlapping boxes on the left represent typical size ranges (on the x-axis) and typical times for populations doublings (on the y-axis) for each type of organism. The boxes to the right represent typical spatial ranges of each organism during its lifetime. Figure adapted from Murphy et al. (1988) as reproduced in Denman et al. (1996).

Implementation of equation (1) to model marine ecosystems typically has not been done. Rather, a truncated form of the equation is used, which usually consists of the elimination of one or more spatial dimensions, e.g., a vertical plane approach, or the assumption of steady state. It is only recently that three-dimensional, time-dependent models have been constructed for marine ecosystems. These models are solved on a predetermined grid using a variety of numerical methods.

A finite difference or finite element approximation to equation (1) assumes that processes are homogeneous over space and time scales that are less than those used for the discrete space intervals and the integration time interval. These smaller scale processes are included through parameterizations, such as that used for diffusion. Also, Eulerian models do not retain information about the characteristics or history of individuals. Rather, biological quantities are usually expressed in terms of concentration, e.g., mg N l^{-1}.

The simulated distributions obtained with an Eulerian model can be compared directly with point measurements obtained from moored instruments, which provides verification of the time evolution of the biological distributions at a specific location. The horizontal and vertical distributions obtained from Eulerian models can be compared with distributions constructed from ship surveys or satellite measurements.

Lagrangian Models

Lagrangian models provide an approach that allows trajectories of particles to be tracked over time. This allows determination of likely transport pathways and of residence times. Lagrangian models are of the form:

$$\frac{d\vec{X}}{dt} = \vec{U}(x,y,z,t) + \vec{U}_b(x,y,z,t) \qquad (2)$$

where the time rate of change in the location $(\vec{X})$ of a particle is determined by the physical advective field $[\vec{U}(x,y,z,t)]$ and biological advection $[\vec{U}_b(x,y,z,t)]$ Biological advection consists of directed horizontal swimming, vertical migration, and sinking.

A Lagrangian modeling approach preserves information on the time history of individuals as they move along a trajectory. If equation (2) is modified such that an additional dimension such as animal age is included, then it is possible to track the development of an individual in space and time. Furthermore, this individual-based approach may be formulated to allow for interactions among individual organisms (DeAngelis and Gross, 1992).

Combined Models

A combined model is one that uses an Eulerian approach to establish the distribution of some property through which a particle then moves. In most cases, an Eulerian model is used to provide circulation fields through which biological particles move. Eulerian models can also be used to provide distributions of passive (no behavior) biological quantities, such as phytoplankton. Then non-passive biological quantities, such as zooplankton or fish predators which have behaviors, can be tracked through the simulated phytoplankton (prey) distribution. This latter approach is used when modeling nektonic populations. In either case, techniques that allow for interpolation of information from the Eulerian grid to the location of the Lagrangian particle are needed.

Structured Versus Unstructured Models

The mathematical models used by Riley (1946, 1947) were formulated such that no distinction was made between species of phytoplankton or zooplankton. Rather these were modeled as homogeneous populations and rates applied to these components were assumed to be representative of average conditions. The structure of these first models was in large part determined by the available data sets, which, in general, were not of sufficient resolution to warrant complex models or complex formulations for the model components. Moreover, the objective of these models was to investigate the processes that control seasonal changes in the general plankton community composition.

As understanding and measurement capability of marine ecosystems have advanced, ecosystem models have undergone an evolution from the initial bulk approach models to models that include structure within the various components. This has provided more realism to the models and has allowed marine plankton models to remain current with the level of understanding of how marine systems function. These models allow investigation of processes that control changes in phytoplankton standing stock or specific species.

By adding structure based on size or animal stage, distinct features of a population, such as a feeding or migration behavior, can be isolated in a model. The disadvantage of adding increasing levels of complexity within ecosystem components is that more knowledge is needed to adequately parameterize the model processes. For example, physiological rates, behavioral characteristics, and growth forms for the different sizes or stages need to be measured. Often it is the available measurements that determine whether or not a model is size- or stage-structured more so than the research questions being posed. For example, measurements of marine zooplankton are typically made on the basis of animal stage; measurements of benthic invertebrates or marine phytoplankton are typically done on the basis of size.

An additional type of structure that can be included in marine ecosystem is an explicit description of animal behavior. This process is generally included as part of the vertical advection term in equation (1), as a type of vertical migration that occurs in response to light or some other environmental cue. However, behavior can be included via other model processes, such as through the selection of food or through reproductive strategies. The inclusion of behavior allows investigation of processes that control changes in specific zooplankton species as opposed to simply determining processes underlying changes in zooplankton standing stock. However, inclusion of behavior assumes that data sufficient to parameterize the particular processes are available.

Status of Ecosystem Modeling for Coastal Marine Systems

Many biological models have been developed and implemented for a variety of coastal marine environments (see Hofmann and Lascara, in press b for a review). Overall, these models have given improved understanding of the processes regulating biological production in coastal marine systems. Of these models, only a few include circulation as well as biological components, and only a subset of these have prediction as an objective. Recently, the potential of the coastal marine ecosystem models that attempt predictions was assessed (Hofmann and Lascara, in press a), and it was found that the simulated distributions were less than satisfactory when viewed as predictions. The poor predictive power of these models was attributed to several factors. The three primary factors are discussed below.

Coastal marine models that include circulation and biological components generally have many key variables and span multiple time and space scales. The identification, acquisition, and incorporation of appropriate data sets to be used for model development, implementation, and validation is a daunting task. Most of the existing coupled physical-biological models are the result of multidisciplinary oceanographic programs, which provide large data sets but encompass a limited range of space and time scales. Often these programs only sample, albeit intensively, a single realization of an event, which does not provide independent data sets for model calibration and verification. Furthermore, even the most comprehensive multidisciplinary oceanographic program does not provide truly synoptic coverage of the many biological components that are required for ecosystem models. In this sense, the vast amount of data that are needed to construct coupled physical-biological models limits the number and type that can be developed.

A persistent limitation of physical-biological models is that the circulation models used were not designed *a priori* to be used with biological models. In many cases, the mismatch in the space and time scales treated by the two models is the reason given for discrepancies between the simulated and observed biological distributions. Therefore, one way in which the area of coastal ecosystem modeling can be advanced is to develop circulation models with the intent of applying them to interdisciplinary modeling studies.

The biological models themselves are limited both by conceptual understanding and the ability to measure key dynamical processes. There are no governing equations grounded in conservation principles analogous to the Navier-Stokes equations that can be used to describe biological dynamics. Moreover, model parameterization in many cases is *ad hoc*, due to a lack of methods and technology to measure *in-situ* physiological processes. Thus, this lack of understanding and ability to measure biological processes contributes to differences in simulated and observed biological distributions.

Status of Ecosystem Modeling for the Gulf of Maine

Prior to the development of any ecosystem model for the Gulf of Maine, there must be the existence of an over-arching conceptual model for the system. This is a must if predictive ecosystem model(s) are to be a goal for the Gulf of Maine program. At present, such an over-arching conceptual model(s) is not available. Therefore, before proceeding further, the Gulf of Maine program should invest resources and effort in constructing a conceptual model that can be used to guide ecological modeling research in this region.

The issue of data availability is related to the development of the over-arching conceptual model. The many papers in the literature that consider various aspects of the biology and physics of the Gulf of Maine (see the Gulf of Maine Bibliography Listings) show clearly that much information has been obtained for this system and that much effort has been focused on trying to understand the controlling processes in this system. However, whether or not these data sets have been collected in such a way as to be useful for ecosystem model development, verification, and calibration remains to be determined. The types of data that are needed for ecosystem model development include measurements of biological rates, age or size specific physiological processes, and environmental effects, in addition to traditional standing stock measurements. At present, the availability of such a suite measurements for the Gulf of Maine ecosystem is limited.

There has been considerable progress in the development of models for some aspects of the Gulf of Maine system. In particular, there has been much progress in the development of circulation models (e.g., Greenberg and Lynch, 1992) that include the Gulf of Maine, as well as part of the adjoining coastal ocean. The circulation models have good horizontal resolution and include realistic physics; however, the adequacy of the circulation model for ecosystem studies is still to be assessed. As mentioned previously, most circulation models are not designed from the outset to be used with biological modeling studies and, therefore, may not include the resolution or dynamics that are important for biological processes. For example, current circulation models for the Gulf of Maine do not include an explicit mixed layer model; therefore, it is important at this point for those doing the physical and biological models to work together and also work with those doing the experimental and field measurements. This communication is essential for the development of a Gulf of Maine ecosystem model.

Some progress has been made in using Lagrangian models to investigate biological transport patterns and residence times for portions of the Gulf of Maine system (e.g., Werner et al., 1993). These simulations illustrate the importance of the circulation in determining the distribution and retention of larval fish on Georges Bank. The majority of these simulations have been with passive particles, but simulations that have included simple formulations for behavior and physiological processes have been done. Future efforts should be directed at improving the biological realism of these models, especially given the useful results that can be obtained with Lagrangian calculations. This, however, will require data sets that describe the biological growth and development processes as functions of environmental conditions, such as temperature and food supply.

Limited progress has been made on the development of lower trophic level models for the Gulf of Maine. Future development of such models is expected since this has been identified as a primary goal for the overall program. A consideration in the development of an ecosystem is whether to modify an existing model from another system or to develop a model explicitly for the Gulf of Maine. The latter is preferable, but the former is what often happens. The development of lower trophic level models requires that data be available and that the over-arching conceptual model be in existence. Without these, the model may not be representative of the Gulf of Maine system.

Models that extend beyond the lower trophic levels have not been done for the Gulf of Maine system. These models, like the others mentioned above, require considerable data and an over-arching conceptual framework; however, an important consideration for top predator models is how they interface with the circulation and lower trophic level models. The space and time scales encompassed by models for top predators differ from those typically included in circulation and lower trophic level models. Again, this illustrates the need for cooperation among the various components of the Gulf of Maine field and modeling programs for a holistic approach to be taken for the development of Gulf of Maine ecosystem models.

Summary

In order for ecosystem models with predictive potential to be developed for the Gulf of Maine or any other coastal marine system, circulation models that have been developed from the outset with the intent of applying them to interdisciplinary modeling studies are needed. The circulation models need to resolve the vertical current structure, mixed layer dynamics, as well as the larger scale advective flows.

An important aspect of furthering the development of ecosystem models for the Gulf of Maine is recognizing the need for interdisciplinary multi-scale observa-

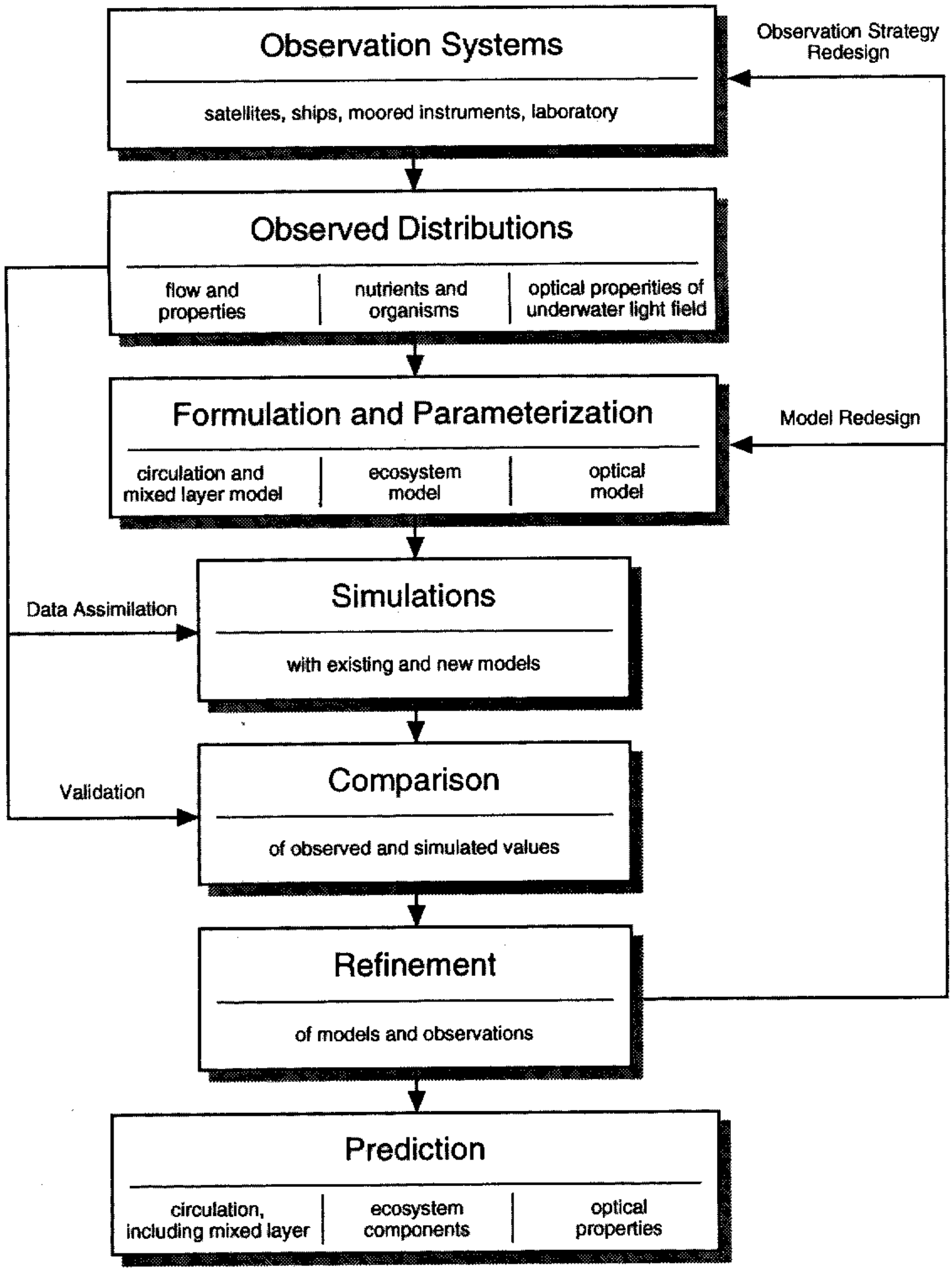


Figure 2. A conceptual approach for developing marine ecosystem models. Figure from Hofmann and Lascara (in press a).

tional and experimental programs. High priority needs to be given to the development of sampling and observations programs that will provide integrated data sets at a variety of space and time scales; however, the availability of multiple data types will necessitate the development of techniques for inputting these data into the ecosystem and circulation models. Therefore, the Gulf of Maine program should invest some resources in the development of data assimilation techniques for biological models that will allow input of a variety of data sets such that consistency with the model dynamics is maintained. Data assimilation techniques for biological models are beginning to be developed and the results from these data assimilative models are encouraging; however, much remains to be done in this area.

The Gulf of Maine program should take advantage of developments in biological instrumentation and measurement techniques. This program has the potential for providing a framework for testing new approaches for acquiring interdisciplinary data that can be used with ecosystem models. One possibility is for the Gulf of Maine program to invest resources in developing models that can be used in quasi-real time to integrate and synthesize data as it is collected during field programs.

Finally, advances in prediction of coastal marine ecosystems will come once predictive models for this system are viewed as a series of interlinking circulation, ecosystem, and optical models that are in turn interfaced with a wide range of measurement systems (Figure 2, previous page). The development of such a hierarchy of models will require considerable cooperation among many individuals.

Acknowledgments

Support for completion of this paper was provided by the National Aeronautics and Space Administration and the Regional Association for Research on the Gulf of Maine. Computer resources and facilities were provided by the Center for Coastal Physical Oceanography at Old Dominion University. Thanks are extended to J. Morgan for assistance in preparing this paper for publication.

References

DeAngelis, D. L. and L. J. Gross. 1992. *Individual-Based Models and Approaches in Ecology*. Chapman and Hall.

Denman, K., E. Hofmann and H. Marchant. 1996. Marine biotic responses to environmental change and feedbacks to climate. In *The Science of Climate Change*, eds. J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenburg and K. Maskell, 486-516. Cambridge: Cambridge University Press.

Denman, K. L. and T. M. Powell. 1984. Effects of physical processes on planktonic ecosystems in the coastal ocean. *Oceanography and Marine Biology Annual Review* 22:125-158.

Fasham, M. J. R. and G. T. Evans. 1995. The use of optimization techniques to model marine ecosystem dynamics at the JGOFS station at 47° N 20° W. *Philosophical Transactions of the Royal Society of London B* 348:203-209.

Greenberg, D. A. and D. R. Lynch. 1992. Review: Gulf of Maine Circulation Modeling. In *Proceedings of the Gulf of Maine Scientific Workshop*, eds. J. Wiggin and C.N.K. Mooers, 125-140. Boston: Urban Harbors Institute, University of Massachusetts at Boston.

Hofmann, E. E. and C. M. Lascara. in press a. A review of predictive modeling for coastal marine ecosystems. In *Coastal Ocean Prediction*, ed. C. N. K. Mooers. Estuarine and Coastal Studies Series. American Geophysical Union, Washington, D.C., in press a.

Hofmann, E. E. and C. M. Lascara. in press b. An overview of interdisciplinary modeling for marine ecosystems. In *The Sea: Volume 10 – The Global Coastal Ocean: Processes and Methods*, eds. K. H. Brink and A. Robinson, New York: John Wiley & Sons, Inc., in press b.

Kierstead, H. and L. B. Slobodkin. 1953. The size of water masses containing plankton blooms. *J. of Marine Research* 12:141-147.

Lawson, L. M., E. E. Hofmann and Y. H. Spitz. 1996. A data assimilation technique applied to a marine ecosystem model. *Deep-Sea Research* 43:625-651.

Lawson, L. M., Y. H. Spitz, E. E. Hofmann and R. B. Long. 1995. A data assimilation technique applied to a predator-prey model. *Bulletin of Mathematical Biology* 57:593-617.

Legendre, L. and S. Demers. 1984. Towards dynamic biological oceanography and limnology. *Canadian J. of Fisheries and Aquatic Science* 41:2-19.

Matear, R. J. 1995. Parameter optimization and analysis of ecosystem models using simulated annealing: A case study at Station P. *J. of Marine Research* 53:571-607.

Murphy, E. J., D. J. Morris, J. L. Watkins and J. Priddle. 1988. Scales of interaction between Antarctic krill and the environment. In *Antarctic Ocean Resources and Variability*, ed. D. Sahrhage, 120-130. Berlin: Springer-Verlag.

Nihoul, J. C. J. and S. Djenidi. 1991. Hierarchy and scales in marine ecohydrodynamics. *Earth-Science Review* 31:255-277.

Riley, G. A. 1946. Factors controlling phytoplankton populations on Georges Bank. *J. of Marine Research* 6:54-73.

Riley, G. A. 1947. A theoretical analysis of the zooplankton population on Georges Bank. *J. of Marine Research* 6:104-113.

Sverdrup, H. U. 1953. On Conditions for the vernal blooming of phytoplankton. *J. Conseil international pour l'Exploration de la Mer* 18:287-295.

Walsh, J. J. 1975. A spatial simulation model of the Peru upwelling ecosystem. *Deep-Sea Research* 21:201-236.

Werner, F. E., F. H. Page, D. R. Lynch, J. W. Loder, R. G. Lough, R. I. Perry, D. A. Greenberg and M. M. Sinclair. 1993. Influences of mean advection and simple behavior on the distribution of cod and haddock early life stages on Georges Bank. *Fisheries Oceanography* 2:43-64.

Wroblewski, J. S. 1977. A model of phytoplankton plume formation during variable Oregon upwelling. *J. of Marine Research* 35:357-394.

Wroblewski, J. S. and J. J. O'Brien. 1976. A spatial model of phytoplankton patchiness. *Marine Biology* 35:161-175.

Wroblewski, J. S., J. J. O'Brien and T. Platt. 1975. On the physical and biological scales of phytoplankton patchiness in the ocean. *Mémoires Société Royale des Sciences de Liège* 7:43-57.

Ecosystem Modeling of European Regional Seas: Applicable for the Gulf of Maine?

Job W. Baretta

Ecological Modelling Centre

Joint Department of the Danish Hydraulic Institute and VKI

Abstract

An overview is given of the European Regional Seas Model. This model dynamically simulates the cycling of carbon and the macronutrients N, P and Si in the pelagic and benthic food webs of the North Sea, forced by light, temperature and both advective and diffusive transport processes. The model has been implemented both in a coarse spatial resolution, dividing the North Sea into ten boxes, the ICES boxes, of which the five deepest have been resolved into surface (0 - 30 m) and deep (30 m - bottom) boxes, as well as into 1° x 1° boxes, the ICES grid. At the open boundaries, time series have been prescribed for dissolved and particulate nutrients. River loads of nutrients for all the major rivers discharging into the North Sea have been prescribed at the highest frequency available, ranging from weekly to annual. A general circulation model has been used to aggregate the daily exchange volumes across the box boundaries into daily exchange coefficients. From these the advective transports of dissolved and suspended constituents are calculated. Vertical transport is in the form of sinking and sedimentation for particulates and in the form of turbulent diffusion for dissolved constituents. The physical submodel contains all site-dependent information, whereas the biological/chemical submodels have been constructed not to be site-specific. The biological variables are represented as functional groups expressed in units of organic carbon and the chemical variables as the variable internal pools in the biological variables and as the dissolved inorganic pools in water and sediment, expressed in units of N, P and Si. The model code has been developed in a software environment (SESAME), especially developed for enabling the development and application of complex model systems in a modular way by a consortium of institutes, each focusing on different aspects of the ecosystem and developing different parts of the code. The concept of non-structured populations aggregated into functional groups has worked well for the lower trophic levels, which almost exclusively comprise organism groups in which biomass growth means more individuals with the same characteristics. For the higher trophic levels, where biomass growth of a population primarily expresses itself as increasing size of the individual population members, with resultant changes in physiology, trophic interactions etc., the unstructured approach fails. As 80 - 90% of the cycling of carbon and nutrients in marine ecosystems goes on in the microbial food web, a less than accurate representation of the role of the higher trophic levels in carbon and nutrient cycling does not affect the overall results dramatically. Examples are given of how this approach might be applicable to regional seas in other parts of the world.

Introduction

In the Marine Science and Technology program (MAST) of the European Union (EU) a group of marine research institutes from countries around the North Sea has initiated the project European Regional Seas Ecosystem Model (ERSEM) to construct, calibrate and verify an ecosystem model of the North Sea.

The participants in the second part of this project are:

Netherlands Institute for Sea Research (NIOZ), Texel, The Netherlands
Plymouth Marine Laboratory, Plymouth, Great Britain
Institut für Meereskunde, Hamburg, Germany
Marine Laboratory Aberdeen, Scotland
University of Aberdeen, Scotland
Strathclyde University, Scotland

Ecological Modelling Centre, joint department of Danish Hydraulic Institute and VKI, Hørsholm, Denmark
Carl von Ossietzky Universität, Oldenburg, Germany

The objective of this project was to provide a basis to support decision-making in environmental quality and biological resource management by developing suites of modules for combination into ecosystem models aimed at answering particular biological and environmental management questions, pertaining to the North Sea. In particular we aimed to address questions that are probably caused by eutrophication effects, such as the seasonal occurrence of anoxic conditions in stratified waters, changes in autotrophic and heterotrophic production and trends in relative nutrient availability.

The model suite integrated the current views on the functioning of marine ecosystems into generic formulations of the processes by which carbon and nutrients (N, P, Si) are cycled in shelf seas, including the associated oxygen dynamics.

Existing Models

Many generic formulations of marine ecological processes already exist and a number of process models of aspects of North Sea dynamics have been published in the scientific literature (cf., Fransz et al., 1991). Many more alternative process models of other marine systems have been published in the scientific literature elsewhere. The existing time-dependent horizontal box models for regions of the North Sea (Fransz and Verhagen, 1985; Mommaerts et al., 1984; Markus et al., 1988) have emphasized biological detail in the pelagic system at the expense of detail in physical structure and transport processes. These, and other models, describe the seasonal cycle of plankton dynamics using vertically integrated equations (cf., Pace et al., 1984); a few models include the vertical structure of the water column (Kiefer and Kremer, 1981; Stigebrandt and Wulff, 1987; Radach and Moll, 1990). To date, only very few attempts have been made to integrate into a single model all the processes which define a total coastal ecosystem (Kremer and Nixon, 1978; Radford, 1979; Baretta and Ruardij, 1988). The difficulty in achieving such a synthesis is to model each process at a similar level of detail, since some system processes have been exhaustively researched and can be modeled with a lot of detail, whereas many other essential system processes have hardly been studied at all and thus only may be modeled very coarsely. As a consequence, there are numerous vertically integrated plankton/nutrients models, but, for example, almost no models of benthic processes, nor of the microbial food web in coastal and shelf ecosystems. Thus there is an urgent need for process studies, especially of the pelagic and benthic small food webs, which contribute significantly to carbon and nutrient cycling.

The ability to simulate nutrient cycling is closely related to the ability to simulate both 'new' and 'regenerated' production. The present models are able to simulate the gross characteristics of the spring plankton production (new production), the order of magnitude of the biomass produced and the timing of the bloom within a range of one to two months (Radach, 1983). Simulation of summer production (regenerated production) and fall blooms (new production) is less successful and in the simulated annual cycle they are usually underestimated. This is partly due to a lack of knowledge about nutrient regeneration, both in the water column and at the sediment-water interface, but mainly to the lack of coupling in the models between biology, chemistry and physics (Jones and Henderson, 1987).

Model Setup

ERSEM, the European Regional Seas Ecosystem Model, is a comprehensive ecosystem model which dynamically simulates the large-scale cycling of organic carbon, oxygen and the macronutrients N, P and Si over the seasonal cycle in the North Sea. The setup of the model is modular (Blackford and Radford, 1995). The model consists of an interlinked set of modules, describing the biological and chemical processes in the stratified or non-stratified water column and in the benthic system, as forced by light and temperature. Physical transport is included by driving the model with the box-aggregated output of a 3-D general circulation model (Lenhart et al., 1995).

The model consists of a coupled set of 70 ordinary differential equations which may be solved by a straightforward explicit method (rectilinear integration) or by an implicit fifth order Runge Kutta method.

The model is run on Unix workstations using the simulation modeling package SESAME (Software Environment for Simulation and Analysis of Marine Ecosystems) which has been developed at the Netherlands Institute for Sea Research and which is reported elsewhere (Ruardij et al., 1995).

The ERSEM model is a conventional biomass-based marine ecosystem model in that it contains no new functional groups that have not been included in marine simulation models before (cf., Fransz et al., 1991). It is ambitious in that it includes them all in one model, which is a severe test of the internal consistency of the dynamics of the different functional groups.

An overview of version 5.2 of the ERSEM model, halfway through the project, is given in Baretta et al. (1995). A full description of the model code itself, including the coding conventions, is available from Plymouth Marine Laboratory.

The Biological Submodels

The model adheres to the usual division of biological state variables into functional groups, both in the pelagic submodel and in the benthic submodel (Figure 1, next page), the functional groups not having an internal size structure (except for the fish submodel which has annual cohorts) but each functional group being a size-class. Feeding/grazing relationships are generally restricted to the next-smaller functional groups and the own functional group ('cannibalism').

All biological functional groups in the model without a size structure are modeled using the concept of the 'standard organism'. The universal biological processes of food uptake, respiration, growth, mortality etc. are defined in this concept. The differences between the functional groups mainly lie in the rate constants, which are derived experimentally, from literature or from allometric considerations and in the food components on the uptake side. The predators on each functional group may be different too.

This concept works well for those groups where experimental data usually also are derived from population or even community studies, generally the single-celled components of the system.

When modeling functional groups that represent larger, longer-lived organisms, where experimental data usually refer to individuals, we have a two-fold problem: we have to scale the data from the organismal to the functional group level and we cannot accommodate the fact that biomass increase in those populations mostly is by increasing size of individuals and not by larger numbers of the same size. As most, if not all, weight-specific biological rates decrease with increasing size and age, using averaged specific rates for those groups is not very realistic. A partial solution would be to keep track of the time-varying size-frequency structure within the population.

The phytoplankton groups (picophytoplankton, phytoflagellates, diatoms and inedible phytoplankton) contain internal nutrient pools (luxury uptake), and thus have dynamically varying C:N:P ratios. The consequence of this is that detritus also has variable C:N:P ratios. As there is no internal storage of Si by diatoms, Si uptake is only dependent on the external concentration of reactive silicate. This allows us to make the recycling of detrital material, both in the water column and in the sediments, dependent on the actual C:N:P ratio, thus effectively taking the history of detritus into account when defining the prevailing rate of mineralisation.

The microbial food web, recovering dissolved excretion products, labile organic carbon (LOC) into particulate form, has been resolved in ERSEM in order to quantify its role in nutrient (re)cycling in the system and its role in defining the type of food web that emerges in response to changes in nutrient availability (Legendre and Rassoulzadegan, 1995).

Clearly, modeling the carbon and nutrient cycles in shelf sea systems necessitates the inclusion of benthic/pelagic interactions and hence a benthic system submodel. In ERSEM, the benthic submodel contains a food web model describing carbon cycling and carbon-associated nutrient cycling, a bioturbation/bioirrigation model to calculate the diffusion of dissolved substances and the vertical transport in the sediment of particulate matter dependent on the presence and activity of the benthic biota (Ebenhöh et al., 1995).

Additionally, benthic nutrient dynamics, as dependent on redox conditions and bioturbation/irrigation in the sediment, are described in a benthic nutrient dynamics module (Ruardij and Van Raaphorst, 1995). There, the variable positions of the oxygen-penetration-depth horizon and the sulphide horizon are calculated, and the nutrient flux from or into the sediment by diffusive exchange through the sediment-water interface, which depends on the calculated nutrient profiles in the vertical, is calculated.

The Transport Submodel

The high resolution in biological and chemical dynamics on purpose was not matched by an equivalent spatial resolution in modeling the horizontal and vertical

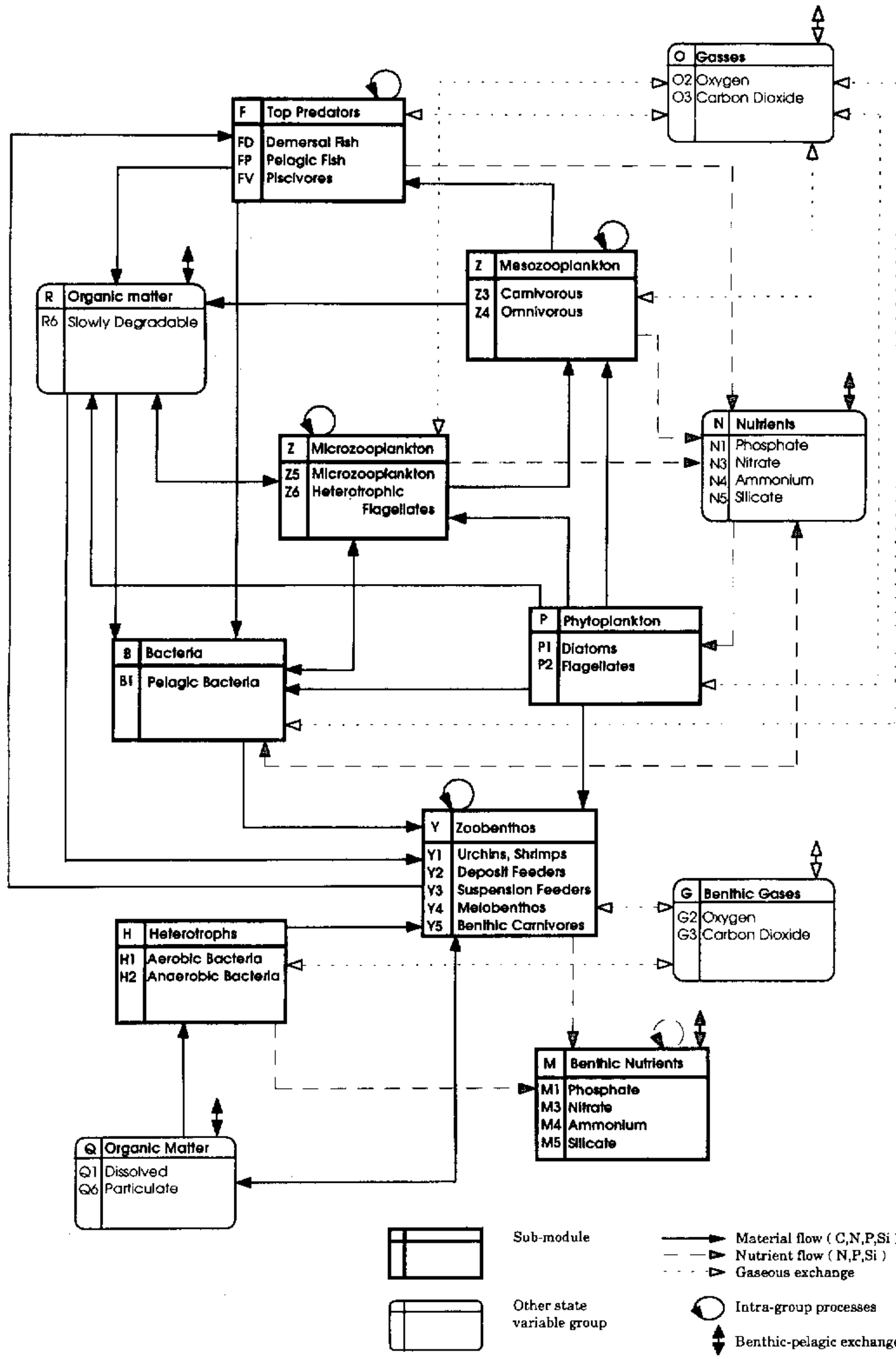


Figure 1. Conceptual diagram of ERSEM.

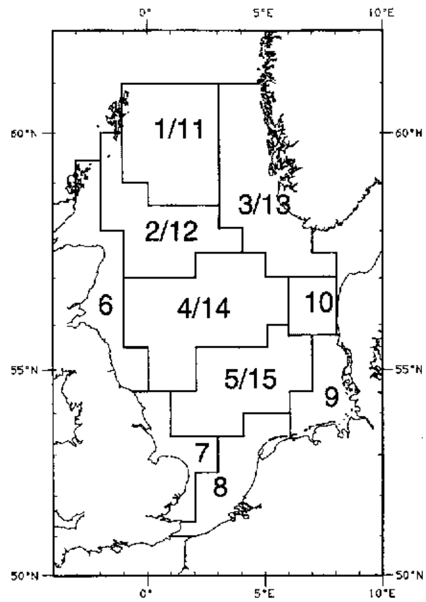


Figure 2. Division of the North Sea into large-scale boxes, similar to the ICES boxes. The ICES box with the German Bight and along the Danish coast is for ERSEM purposes divided into the two boxes 9 and 10.

physical processes in the water column for the first application to the North Sea. Here, the initial choice was made to adopt the ICES boxes (Figure 2) as the spatial compartments. The North Sea accordingly has been divided into 15 boxes. The deeper parts, where thermal stratification always occurs in summer, have been subdivided into five surface and five deep boxes. The five well-mixed coastal and Southern Bight boxes are not subdivided vertically, as tidal mixing generally maintains vertical homogeneity. The coarse horizontal resolution, especially of the regions where large rivers enter the system (boxes 8 and 9) 'dilutes' the high nutrient concentration in the river plume over the whole spatial compartment and thus smears out the on-shore/offshore concentration gradients. Therefore a spatially more refined setup of the model also has been made on a 1° x 1° grid, without changing the vertical resolution.

Horizontal transport is prescribed by daily exchange volumes between boxes, derived from the results of a three-dimensional General Circulation Model for the North Sea (Backhaus, 1985; Pohlmann, 1991). Vertical mixing is prescribed by daily varying exchange coefficients across the boundary between the surface and deep boxes.

The coarseness of especially the vertical resolution inhibits the emergence of detailed dynamical responses of the biological system to high-frequency variability in the vertical mixing, not to mention the importance of mesoscale dynamics on biological productivity for which a fully-coupled 3-D mesoscale-resolving hydrodynamical/biological model will be required.

The model has been structured such that the transport model, which really only consists of time series of daily exchange coefficients across box boundaries, can be replaced by a completely different transport model.

This has made it possible to force the identical biological model with a variety of different hydrodynamical/transport models and thus apply and test the model in different areas. These applications range from the Humber Plume where a two-dimensional vertically integrated tidally averaged model was used (Allen, 1997), a mooring site in the North Sea where a one-dimensional entrainment/detrainment model was used (Van Aken, 1984; Ruardij et al., 1997) to an application where ERSEM has been coupled to an idealized setup of the three-dimensional Princeton Ocean Model for the Adriatic Sea (Zavatarelli, pers. comm.).

Forcing Functions and Boundary Conditions

Water movement is represented indirectly in the model in the form of daily advection coefficients and (vertical) diffusion coefficients, prescribing daily exchanges of water across box boundaries, both horizontally and vertically. With these exchange volumes the transport submodel calculates the transport of dissolved and suspended constituents.

Incident radiation at the water surface is calculated according to Evans and Parslow (1985) from the solar constant as integrated energy over a day, in the absence of cloud cover. Day length is calculated in dependence of the latitude of the center of each spatial compartment. The underwater light climate is calculated from surface irradiance and integrated over the thickness of each box according to Steele (1962), with the extinction coefficient being calculated according to an empirical equation derived by Colijn (1982) from the actual SPM concentration (suspended sediment + detritus + phytoplankton), thus introducing self-shading.

Water temperature is prescribed as an empirical function, dependent on the spatial compartment. This function is derived from the daily temperatures as calculated by a General Circulation Model (Pohlmann, 1991) for the North Sea which have been box-averaged.

The physical forcing of the model thus is climatological, with the exception of the advective and diffusive terms which are for specific years.

A climatological set of boundary conditions for the Channel and Atlantic boundaries has been assembled by the Institut für Meereskunde (IfM) in Hamburg from ICES data.

Modeling Tools

To build such a comprehensive model, which necessarily has a modular structure, we need suitable tools, of which adequate modeling software is the most important one, closely followed by the availability of a model framework defining the overall conceptual model structure. This model framework, defined and distributed at the start of the project, was essential, as the structure of complex ecosystems is rather ill defined; it ensured that all participants were developing their submodels within the same system definition, even though working at different locations.

Simulation software, designed to facilitate ecological modeling, has proved invaluable to the successful completion of complex multidisciplinary studies (Radford, 1971). Radford (1979) used the commercial simulation package 'Continous System Modelling Program' (IBM, 1967) as a computing environment to model the Bristol Channel and Severn Estuary. Baretta and Ruardij (1988) reported on the development of a package known as BAHBOE which they used to construct their Ems and western Wadden Sea models (EON, 1988). The Danish Hydraulic Institute has developed the MIKE system, a software package for modeling aquatic ecosystems in collaboration with VKI (Vested et al., 1991). Delft Hydraulics has developed DELWAQ (Postma, 1988) as a general framework for water quality and ecological modeling.

Of these packages, the BAHBOE package was the most suitable for developing complex models. This package was ported to UNIX and after extensive modifications in response to users wishes renamed SESAME. (Ruardij et al., 1995).

Verification Data

In the period 1988-1989 the U.K. Natural Environment Research Council (NERC) undertook a major project in the North Sea, the North Sea Community Project. A major subproject was to investigate the seasonal cycle in the North Sea by running a 122-station monthly survey for fifteen months. This project has produced a wealth of coherent data, which have been distributed by the British Oceanographic Data Centre (BODC) on a CD-ROM. This data set has been used to verify phytoplankton and nutrient dynamics in all the boxes in the model, except for the northern boxes, which were not covered by the survey.

For these northern boxes (1, 2 and 3) data were made available by Marine Laboratory Aberdeen through the ECOMOD data base of IfM in Hamburg.

The microbial food web module has been refined and partly verified in a collaboration with two other MAST projects, Structure and Function of Ecosystems, and Microbial Element Cycling in Coastal Environments, using data from marine enclosures (Baretta-Bekker et al., 1994; 1995; 1997).

Benthic nutrient dynamics and other aspects of benthic system function have been verified using data from the Integrated North Sea Program (INP), run by the Netherlands Institute for Sea Research (NIOZ) (Ruardij and Van Raaphorst, 1995).

Results

The simulation results at the end of the first phase of the project have been described and analyzed in a number of papers (Baretta-Bekker et al., 1995; Broekhuizen et al., 1995; Bryant et al., 1995; Ebenhöh et al., 1995; Lenhart et al., 1995; Radach and Lenhart, 1995; Ruardij and Van Raaphorst, 1995; Varela et al., 1995) with a concise overview in Baretta et al., 1995.

Major problems at that stage were the lack of biological resolution in the primary producers and the microzooplankton as well as the coarse spatial resolution of the model.

These problems have been addressed in the second phase of the project. The detailed results are being published in the *Journal of Sea Research,* 38(3/4).

Here I confine myself to drawing some overall conclusions with regards to the potential applicability of this modeling approach to other regional seas and especially the Gulf of Maine.

For the North Sea, the status quo is that the ERSEM model (Figures 3 to 7) does reproduce the seasonal dynamics of the macronutrients, the primary producers, the microbial food web and the decomposers, both in the water column and in the benthic system, in response

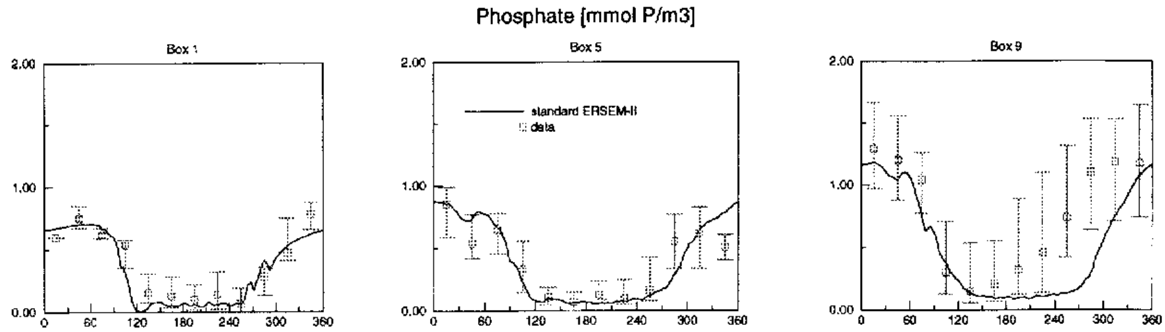


Figure 3. Simulated concentrations throughout the year of PO_4 (mmol $P.m^{-3}$) for the ERSEM boxes with measured values from the BODC and ECOMOD databases.

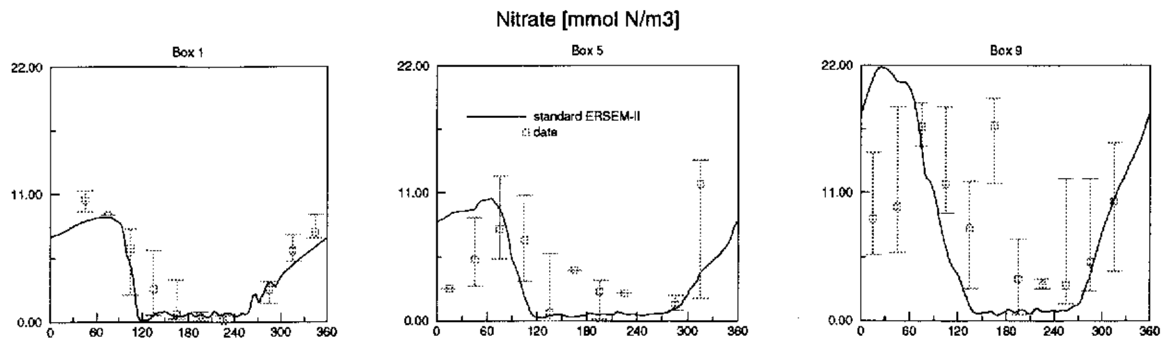


Figure 4. Simulated concentrations throughout the year of NO_3 (mmol $N.m^{-3}$) for the ERSEM boxes with measured values from the BODC and ECOMOD databases.

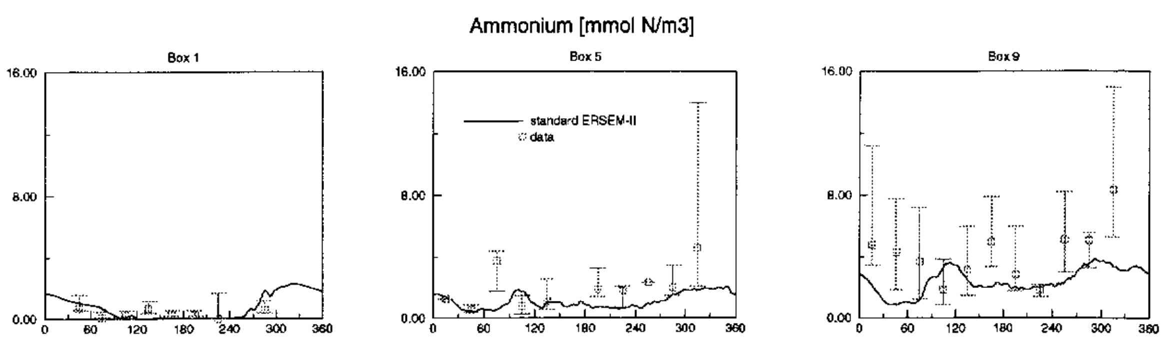


Figure 5. Simulated concentrations throughout the year of NH_4 (mmol $N.m^{-3}$) for the ERSEM boxes with measured values from the BODC and ECOMOD databases.

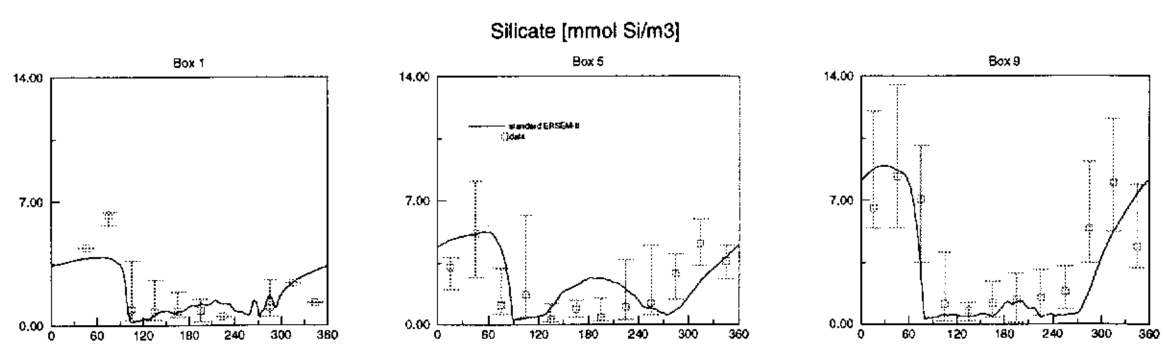


Figure 6. Simulated concentrations throughout the year of SiO_4 (mmol $Si.m^{-3}$) for the ERSEM boxes with measured values from the BODC and ECOMOD databases.

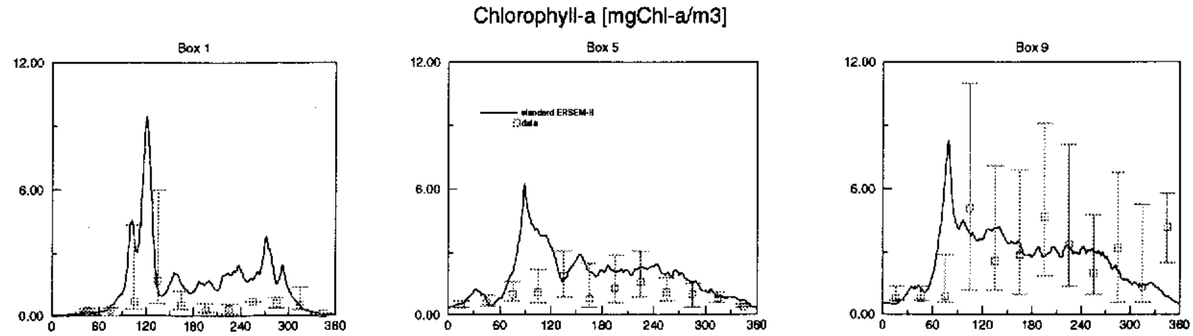


Figure 7. Simulated concentrations throughout the year of chlorophyll (chl-a.m^{-3}) for the ERSEM boxes with measured values from the BODC and ECOMOD databases.

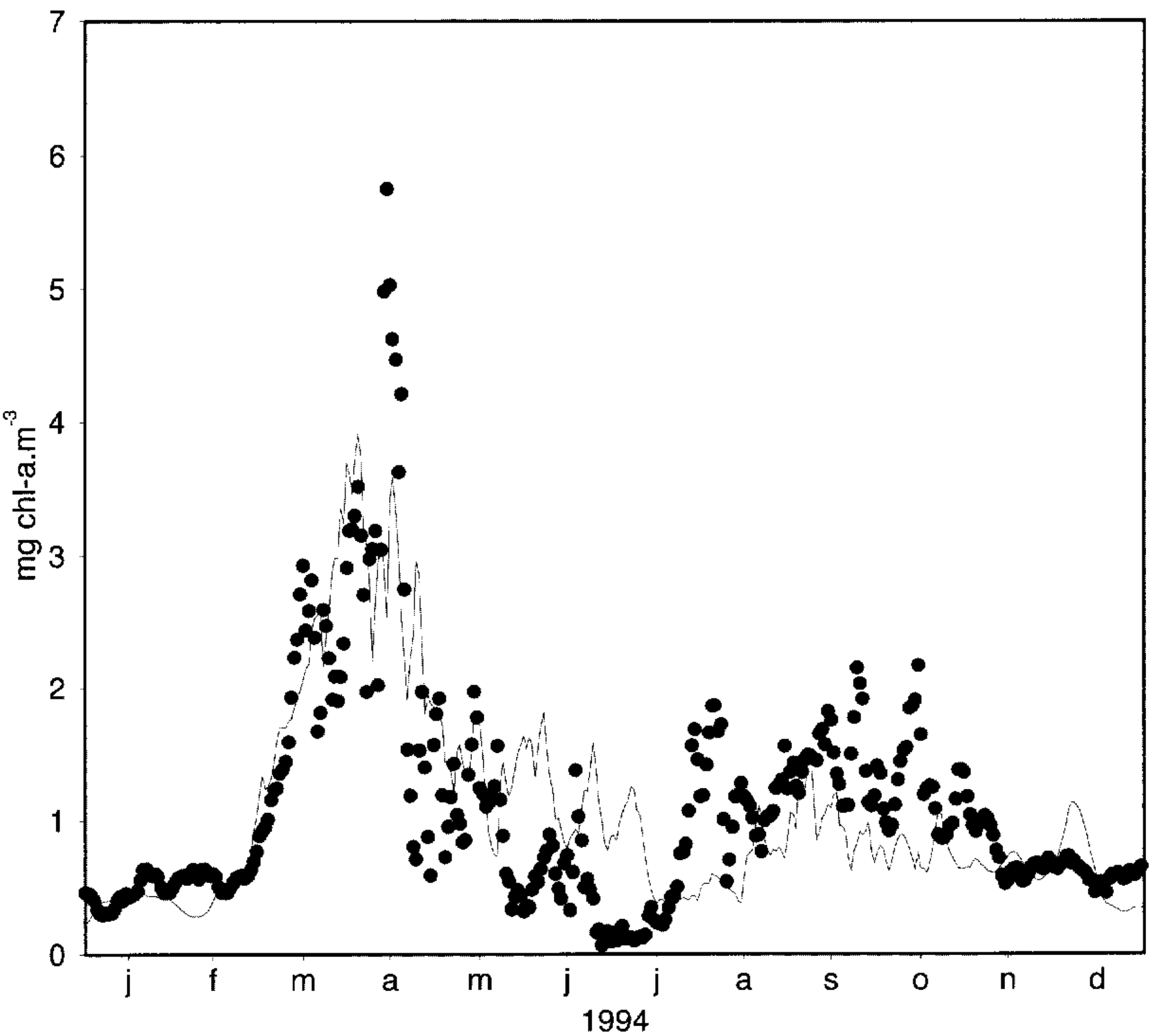


Figure 8. Simulated concentrations of chlorophyll (chl-a.m-3) throughout 1994 in the surface-mixed layer (drawn line) with daily chl-a concentrations at 13 m depth at a mooring site in the Oystergrounds (North Sea) (black dots). The physical model forcing the ERSEM model in this case was a Kraus-Turner entrainment/detrainment model (from Ruardij et al., 1997).

Table 1.
Annual net primary production (g $C.m^{-2}.a^{-1}$) in the ERSEM boxes at different river nutrient loads.

Box	1988	75% 1988	50% 1988	1989	75% 1989	50% 1989
1+11	88	88	87	96	96	96
2+12	99	99	99	101	101	101
3+13	86	86	82	86	86	85
4+14	115	115	112	115	114	112
5+15	126	122	113	132	126	117
6	38	37	37	41	40	39
7	97	91	83	118	111	99
8	152	139	120	156	145	128
9	149	145	126	172	168	143
10	110	108	99	89	88	81

to hydrodynamic forcing to within a factor of 2 of climatological observations, with the correspondence between model results and observations becoming better with increased vertical resolution (Figure 8).

Despite N:P ratios in the riverine nutrient loads from the large continental rivers that exceed 16 : 1 (Mol/Mol) primary production in the North Sea in summer is potentially nitrogen-limited, with N:P ratios below 16:1. Proposals to reduce eutrophication effects by reducing the discharges of phosphorus are therefore unlikely to have the desired effects.

Another model result that may be of interest with regard to coastal zone management is that reducing riverborne nutrients loads by 50% does not lead to a proportional decrease in annual primary production but to a much smaller decrease, even in the spatial compartments where the rivers enter the system (Table 1).

Discussion

Using the available 1988 and 1989 data for verification purposes is only valid assuming that the climatological seasonal cycle in the boundary conditions is a (much) larger signal than the interannual variability. In the absence of a complete set of boundary conditions specifically for 1988-1989 we are forced to make this assumption.

A potentially more serious problem was the lack of reliable synoptic data on suspended particulate matter (SPM), because of the decisive influence of SPM on the underwater light climate. The organic fraction of SPM - detritus- is calculated dynamically in the model, but the inorganic fraction -silt- was prescribed as a time series of monthly averages; this severely restricted the ability of the model to calculate realistic underwater light climates. This problem has been solved by using the results from a sediment transport model as daily time series of SPM concentrations.

The sedimentation of detrital matter onto the sediment is a major transfer pathway of energy and nutrients from the pelagic to the benthic system. The relative (and regionally variable) importance of benthic nutrient regeneration processes to total nutrient fluxes in the North Sea is illustrated by Figure 9. This shows benthic-pelagic N-fluxes to comprise from 20 to 60% of the total N-uptake by phytoplankton. Put in another way, 20 to 60% of phytoplankton production on an annual basis ends up in the sediment, with the actual percentage being inversely related to the depth of the water column. In the absence

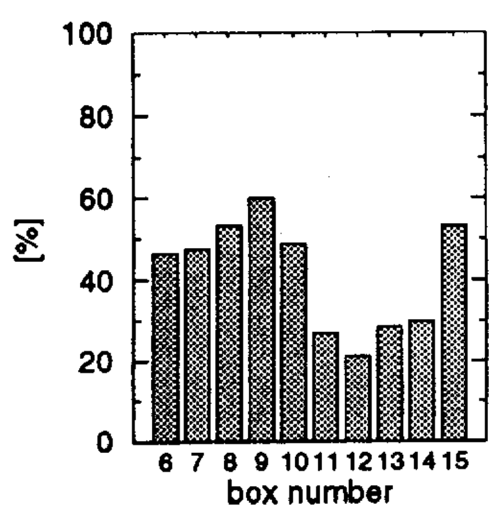


Figure 9. The percentage of nitrogen uptake by phytoplankton mineralized in the benthic system in the various ERSEM boxes (from Ruardij and Van Raaphorst, 1995).

of reliable data on the sedimentation of organic matter, the calculated sedimentation flux cannot be verified directly. Benthic oxygen consumption is dependent on the deposition of organic matter and measured benthic oxygen consumption rates (Cramer, 1990; Van Raaphorst et al., 1992; Nedwell et al., 1993) require 30 to 100 g $C.m^{-2}.a^{-1}$ to be oxidized, which agrees well with the model results (Ruardij and Van Raaphorst, 1995). This allows the conclusion that, on average, input and mineralization of organic matter in North Sea sediments is adequately modeled and that the large-scale benthic/pelagic interactions are captured adequately in the model.

Applicability to the Gulf of Maine

From the proceedings of the first Gulf of Maine scientific workshop it became clear that the development of models coupling physical and biological processes was seen as both desirable and necessary. It also was clear that the high temporal and spatial variability observed in most of the biotic and abiotic components studied in the Gulf remained largely unexplained, which could be taken as another argument to undertake a Gulf-wide modeling effort in order to establish whether such a coupled model can reproduce and explain the observed variability. However, as most of the research efforts in the Gulf of Maine in the biological disciplines appear to be oriented towards the higher trophic levels, with an emphasis on species-oriented work, there is a scarcity of information on the microbial components and their role in the Gulf of Maine. Yet, in view of the many similarities in benthic and pelagic community composition between the North Sea and the Gulf of Maine, there is no apparent reason to assume that the contribution of the uni-cellular components to energy- and nutrient-cycling in the Gulf of Maine would be less than in the North Sea and that the structure and content of an ecosystem model for the Gulf of Maine would have to be different from one developed and tested in the North Sea.

The relative ease with which it has been possible to couple the biological submodels of ERSEM to different hydrodynamical/physical models suggests that it might be feasible to take this approach for the Gulf of Maine as well, especially in view of the availability of a 3-D hydrodynamical model for the entire Gulf of Maine in the model of Lynch et al. (1996).

Acknowledgments

The author thanks the RARGOM steering committee for inviting him, Eugenia Braasch for her help before, during and after the workshop and Don Gordon for making this visit a magical mystery tour of Nova Scotia and New Brunswick. The ERSEM project was partly funded by the EU MAST program, contract MAST-CT90-0021 and MAS2-CT92-0030. The author wishes to stress that ERSEM is a joint creation of all ERSEM participants. Their efforts have resulted in the whole being much more than the sum of the parts.

References

Allen, I., 1997. A modelling study of the ecosystem dynamics and nutrient cycling in the Humber Plume, UK. *J. Sea Res.* 38: in press.

Backhaus, J. O., 1985. A three-dimensional model for the simulation of shelf sea dynamics. *Dt. hydrogr. Z.* 34: 168-262.

Baretta, J. W. and P. Ruardij, (eds.) 1988. Tidal Flat Estuaries, Simulation and analysis of the Ems estuary. *Ecol. Studies 71*, Springer Verlag, Berlin-Heidelberg: 1-353.

Baretta, J. W., W. Ebenhöh and P. Ruardij, 1995. The European Regional Seas Ecosystem Model, a complex marine ecosystem model. *Neth. J. Sea Res.* 33: 233-246.

Baretta-Bekker, J. G., B. Riemann, J. W. Baretta and E. K. Rasmussen, 1994. Testing the microbial loop concept by comparing mesocosm data with output of a dynamical simulation model. *Mar. Ecol. Prog. Ser.* 106: 187-198.

Baretta-Bekker, J. G., J. W. Baretta and E. K. Rasmussen, 1995. The microbial food web in the European Regional Seas Ecosystem Model. *Neth. J. Sea Res.* 33: 363-379.

Baretta-Bekker, J. G., J. W. Baretta, A. Skjoldborg Hansen and B. Riemann, 1997. An improved model of carbon and nutrient dynamics in the microbial food web in marine enclosures. *Aquat. Micr. Ecol.* in press.

Blackford, J. C. and P. J. Radford, 1995. A structure and methodology for marine ecosystem modelling. *Neth. J. Sea Res.* 33: 247-260.

Broekhuizen, N., M. R. Heath, S. J. Hay and W. S. C. Gurney, 1995. Modelling the dynamics of the North Sea's mesozooplankton. *Neth. J. Sea Res.* 33: 381-406.

Bryant, A. D., M. R. Heath, N. Broekhuizen, J. G. Ollason, W. S. C. Gurney and S. Greenstreet, 1995. Modelling the predation, growth and population dynamics of fish within a spatially-resolved shelf-sea ecosystem model. *Neth. J. Sea Res.* 33: 407-421.

Colijn, F., 1982. Light absorption in the waters of the Ems-Dollard estuary and its consequences for the growth of phytoplankton and microphytobenthos. *Neth. J. Sea Res.* 15: 196-216.

Cramer, A., 1990. Seasonal variation in benthic metabolic activity in a frontal system in the North Sea. In *Trophic relationships in the marine environments*, eds. M. Barnes and R. N. Gibson, 54-76. Aberdeen: Aberdeen Univ. Press.

Ebenhöh, W., C. Kohlmeier and P. J. Radford, 1995. The benthic biological model. *Neth. J. Sea Res.* 33: 423-452.

EON, 1988. Ecosysteem model van de westelijke Waddenzee. *NIOZ rapport* 1: 1-88.

Evans, G. T. and J. S. Parslow, 1985. A model of annual plankton cycles. *Biol. Oceanogr.* 3: 327-347.

Fransz, H. G. and J. H. G. Verhagen, 1985. Modelling research on the production cycle of phytoplankton in the Southern Bight of the North Sea in relation to riverborne nutrient load. *Neth. J. Sea Res.* 19: 241-250.

Fransz, H. G., J. P. Mommaerts and G. Radach, 1991. Ecological modelling of the North Sea. *Neth. J. Sea Res.* 28: 67-140.

IBM, 1967. Application program 1967, System 360 Continuous System Modelling Program (360A-CX-16X). Users Manual. IBM.

Jones, R. and E. Henderson, 1987. The dynamics of nutrient regeneration and simulation studies of the nutrient cycle. *J. Cons. int. Expor. Mer* 43: 216-236.

Kiefer, D. A. and J. N. Kremer, 1981. Origins of vertical patterns of phytoplankton and nutrients in the temperate, open ocean: a stratigraphic hypothesis. *DSR 28A*: 1087-1105.

Kremer, J. N. and S. W. Nixon, 1978. A coastal marine ecosystem simulation and analysis. *Ecological studies 24*. Springer Verlag, Berlin-Heidelberg: 1- 217.

Legendre, L. and F. Rassoulzadegan, 1995. Plankton and nutrient dynamics in marine waters. *Ophelia* 41: 153-172.

Lenhart, H. J., G. Radach, J. O. Backhaus and T. Pohlmann, 1995. Simulations of the North Sea circulation, its variability and its implementations as hydrodynamic forcing in ERSEM. *Neth. J. Sea Res.* 33: 271-299.

Lynch, D. R., J. T. C. Ip, C. E. Namie and F. E. Werner, 1996. Comprehensive coastal circulation model with application to the Gulf of Maine. *Cont. Shelf Res.*, 16: 875-906.

Markus, A. A., P. C. G. Glas and A. Van der Giessen, 1988. A simulation model of phytoplankton and water quality in the Southern Bight of the North Sea. *ICES-paper CM1988/C:44*, Hydrography Committee.

Mommaerts, J. P., G. Pichot, J. Ozer and Y. Adam, 1984. Nitrogen cycling and budget in Belgian coastal waters: North Sea areas with and without river inputs. *Rapp. P.-v. Réun. Cons. int. Explor. Mer* 183: 57-69.

Nedwell, D. D., R. J. Parker, A. C. Upton and D. J. Assinder, 1993. Seasonal fluxes across the sediment-water interface, and processes within sediments. *Phil. Trans. R. Soc.* 343: 519-531.

Pace, M. L., J. E. Glasser and L. R. Pomroy, 1984. A simulation analysis of continental shelf food webs. *Mar. Biol.* 82: 47-63.

Pohlmann, T., 1991. Untersuchung hydro- und thermodynamischer Prozesse in der Nordsee mit einem dreidimensionalen numerischen Modell, Dissertation Uni-Hamburg.

Postma, L., 1988. Delwag. User's Manual. Delft Hydraulics: 1-180.

Radach, G., 1983. Simulation of phytoplankton dynamics and their interactions with other system components during FLEX'76. In *North Sea Dynamics*, eds. J. Sündermann and W. Lenz, 584-610. Berlin-Heidelberg:Springer Verlag.

Radach G. and H. J. Lenhart, 1995. Nutrient dynamics in the North Sea: fluxes and budgets in the water column, derived from ERSEM. *Neth. J. Sea Res.* 33: 301-335.

Radach, G. and A. Moll, 1990. State of the art in algal bloom modelling. In *Eutrophication and algal blooms in North Sea coastal zones, the Baltic and adjacent areas*, eds. C. Lancelot, G. Billen and H. Barth. Water Pollution Research Reports 12: 115-149.

Radford, P. J., 1971. The simulation language as an aid to ecological modelling. In *Mathematical Models in Ecology*, ed. J. N. R. Jeffers, 277-296. Proc. Symp. Bristol Ecological Society.

Radford, P. J., 1979. Some aspects of an estuarine ecosystem model GEMBASE. In *State of the art in Ecological Modelling*, ed. S.E. Jørgensen. Proc. ISEM conference on ecological Modelling, Copenhagen, 1978. International Society for Ecological Modelling pub.: 301-322.

Ruardij, P. and W. Van Raaphorst, 1995. Benthic nutrient regeneration in the ERSEM ecosystem model of the North Sea. *Neth. J. Sea Res.* 33: 453-483.

Ruardij, P., J. W. Baretta and J. G. Baretta-Bekker, 1995. SESAME, Software Environment for Simulation and Analysis of Marine Ecosystems in general and for spatially resolved ecosystems in particular. *Neth. J. Sea Res.* 33: 261-270.

Ruardij, P., H. Van Haren and H. Ridderinkhof, 1997. The impact of thermal stratification on phytoplankton and nutrient dynamics in shelf seas: a model study. *J. Sea Res.* 38: in press.

Steele, 1962. Environmental control of photosynthesis in the sea. *Limnol. Oceanogr.* 7: 137-150.

Stigebrandt, A. and F. Wulff, 1987. A model for the dynamics of nutrients and oxygen in the Baltic proper. *J. Mar. Res.* 45: 729-757.

Van Aken, H., 1984. A one-dimensional mixed-layer model for stratified seas with tide- and wind-induced mixing. *Deutsches Hydrographisches Zeitschrift* 37: 3-27.

Van Raaphorst, W., H. T. Kloosterhuis, E. M. Berghuis, A. J. M. Gieles, J. F. P. Malschaert and G. J. Van Noort, 1992. Nitrogen cycling in two types of sediments of the southern North Sea (Frisian Front, Broad Fourteens): field data and mesocosm results. *Neth. J. Sea Res.* 26: 25-52.

Varela, R. A., A. Cruzado and J. E. Gabaldón, 1995. Modelling primary production in the North Sea using the European Regional Seas Ecosystem Model. *Neth. J. Sea Res.* 33: 337-361.

Vested, H. J., O. K. Jensen, A. C. Ellegaard, H. K. Bach and E. K. Rasmussen, 1991. Circulation modelling and water quality prediction: Proceedings on the 2nd international conference on estuarine and coastal modeling, Florida, 1991: 317-331.

Aquaculture in the Gulf of Maine

Joseph A. Brown
Memorial University of Newfoundland

Abstract

Aquaculture continues to be the fastest growing sector of the world's fishery. Latest figures from the Food and Agriculture Organization of the United Nations show that between 1994-1995 aquaculture grew between 11 and 12%. This resulted in an increase of over three billion dollars (U.S.) to a total revenue of over $33.53 billion dollars (U.S.). This increase continues a trend from the early 1980s and is predicted to continue well into the next century. This prediction is based on the observation of a stabilization of the world's capture fishery at around 100 million tons and an increasing demand for seafood as the world's population grows. Thus production from aquaculture will have to expand to meet the increased demand.

North America's contribution to world aquaculture accounted for slightly over 3% which pales in comparison to Asia's 87% contribution. Currently 13% of the seafood consumed in the United States is produced by the aquaculture industry. This percentage is forecast to double over the next 10 years.

Aquaculture within the Gulf of Maine was worth over $146 million (U.S.) in 1995 up from $112 million in 1992. Aquaculture production in the Bay of Fundy (New Brunswick) led the way in 1995, followed by Maine, Massachusetts and New Hampshire. The dominant species in New Brunswick and Maine are Atlantic salmon and steelhead. The dominant species in New Hampshire and Massachusetts are trout and Northern Quahog, respectively. Other species of commercial importance are rainbow trout, Eastern oyster, hybrid striped bass, nori, baitfish, scallops and mussels.

There is increasing interest in developing new species for the aquaculture industry within the Gulf of Maine. Research and development projects have begun on halibut, haddock, winter flounder, yellowtail flounder and sea scallops in New Brunswick. Maine is looking at Atlantic cod, haddock, halibut, sea scallops and surf clams; while New Hampshire and Massachusetts are looking at winter flounder, haddock, summer flounder, and witch flounder. In Maine, the interest in the culture of cod has been focused on enhancing this resource through the release of juvenile cod in the coastal areas of the state. In my talk, I will review Norwegian experiences over the last decade as well as recent successes in Japan on their marine enhancement program. The situation in Newfoundland with regard to cod enhancement using larval tagging/release, or grow and release, will also be reviewed. Survival of released cod and their impacts on wild populations will be discussed in conjunction with the impact of cultured salmon on wild salmon as outlined below.

The steady increase in salmonid production has resulted from an increase in the number of cages per site as well as an increase in the number of sites. This has led to a concern over the potential environmental impacts of this activity and, in response to this concern, New Brunswick and the State of Maine initiated monitoring programs. Initial results indicate that benthic impacts are minimal at 2/3rds of the leases. The second impact of concern is that of "escapees" on wild populations of salmonids.

Escapees from pens can impact natural populations of salmonids in three ways: disease, genetics, and physical disturbance. The disease problem has usually been the result of introductions of farmed stock from hatcheries which had a history of disease. Another concern is of genetic impact which has received much theoretical attention but has been difficult to demonstrate from empirical work. The potential genetic impact of farmed fish could result in "less adapted" offspring and hence lower natural productivity. The physical distur-

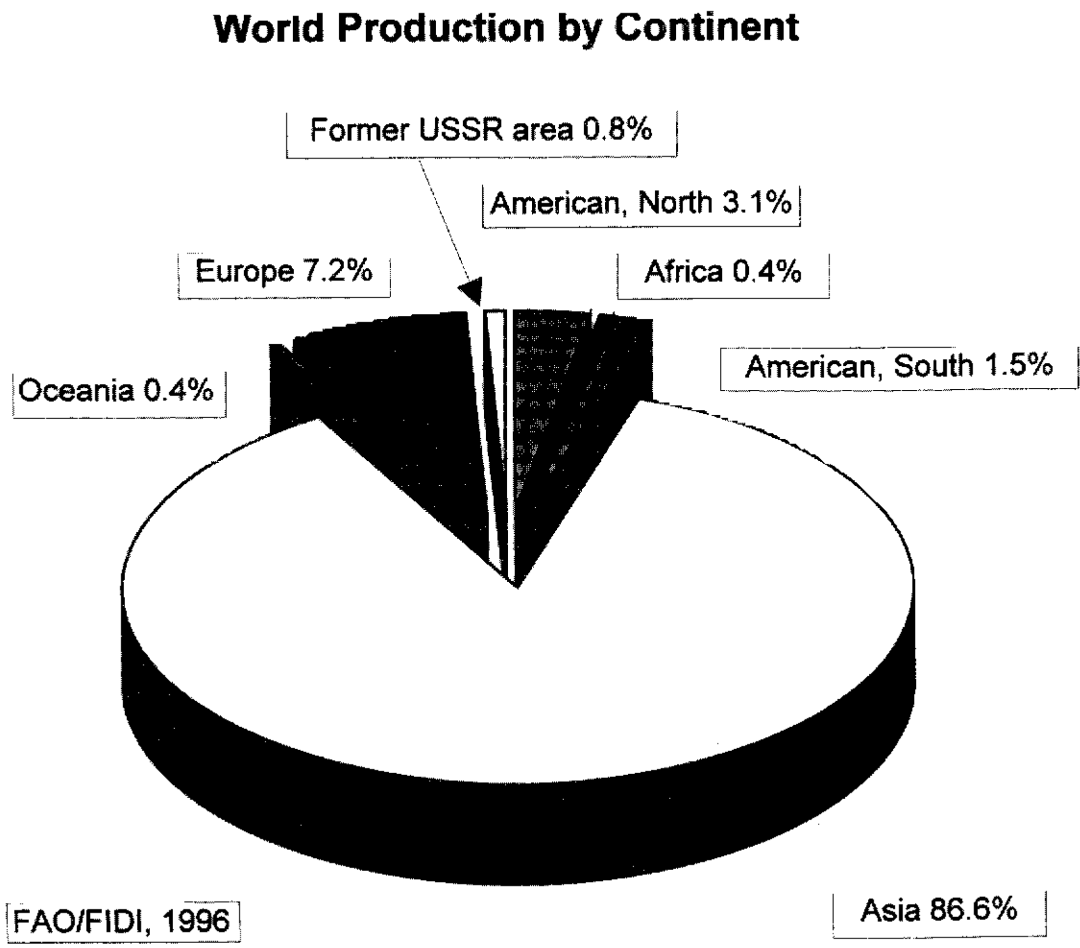


Figure 1. World aquaculture production (%) shown by continent.

bance concern centers around the disturbance of high numbers of farmed fish on the wild fish in the spawning areas. This could lead to behavioral problems associated with spawning or physical disturbance of the "redds". The Norwegian experience with both escapee's and salmon enhancement impact on wild populations will be discussed.

Introduction

World aquaculture production continues to increase in both quantity and quality in every country which has an industry, except the former USSR. According to the latest figures of the Food and Agriculture Organization (FAO) of the United Nations, the value of aquaculture rose by over 3 billion dollars (U.S.) from 1994 - 1995 and the quantity of product rose by over 11% to 25.46 million tons (*Fish Farming International*, 23:7, 1996). All sectors of the industry, marine, freshwater, plants, finfish and shellfish, recorded increases, and expectations are that aquaculture will continue to increase through the next decade and beyond.

For the purpose of this paper I will use the FAO's definition of aquaculture, which is the farming of aquatic organisms, including fish, mollusks, crustaceans and aquatic plants. Farming implies intervention in the rearing process to enhance production and it also means that some form of individual or corporate ownership of the organisms being produced is in place (Hempel 1993). Thus, products that are harvested by an individual or corporation that has owned them throughout their rearing is, by definition aquaculture, while aquatic organisms that are exploited by the public as a common property resource are considered as harvest fisheries. These FAO definitions were established in 1992 (FAO, 1992) and reflected the fact that, for the first time, this

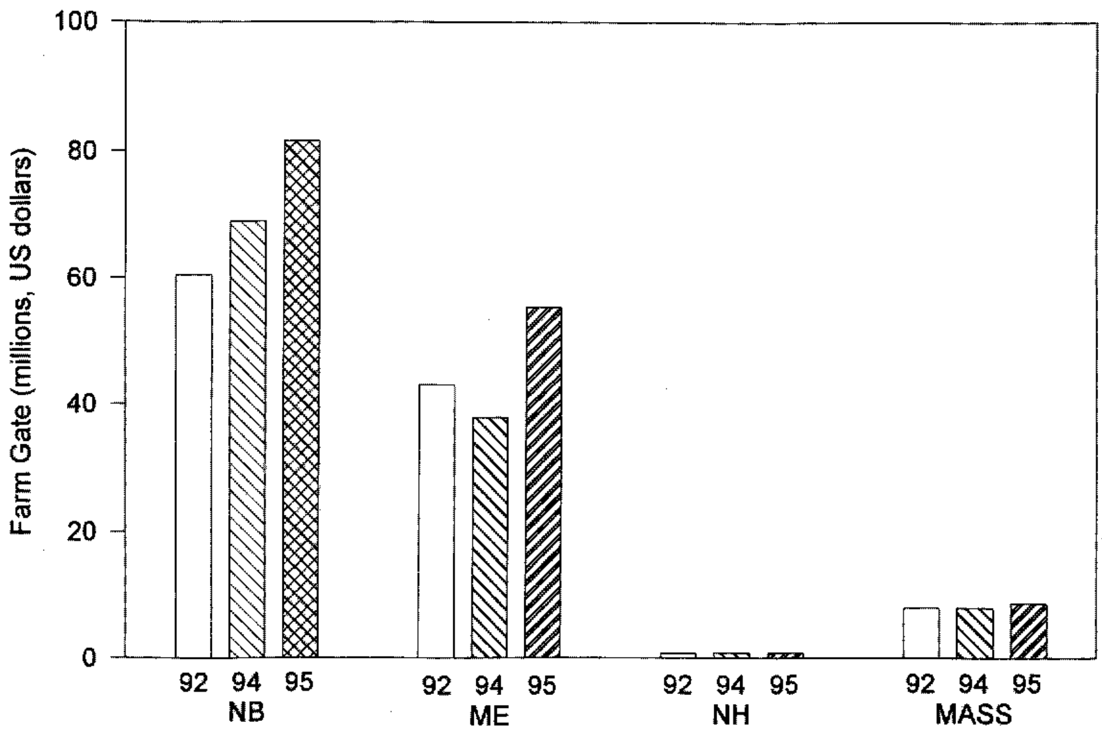


Figure 2. Farm gate (million dollars, U.S.) over the period 1992 - 1995 for New Brunswick (NB), Maine (ME), New Hampshire (NH) and Massachusetts (MA).

organization began keeping statistics and publishing annual reports on aquaculture. I think this point alone indicates that aquaculture as a global industry is young, even though in Asia aquaculture has been practiced for over 2,000 years.

In the rest of this paper I am going to briefly review the expectations for aquaculture production, the current status of aquaculture in North America and the past and current status of aquaculture in the Gulf of Maine. I will follow this by looking at future developments with regards to diversifying the industry in the Gulf, review current enhancement efforts in Maine with a look towards the future for enhancement, and review the potential for interactions between wild and cultured fish.

World and North American Trends

Latest figures from the FAO show that between 1994-1995 aquaculture grew between 11 - 12%. This resulted in an increase of over three billion dollars (U.S.) to a total revenue of over $33.53 billion dollars (U.S.). This increase continues a trend from the early 1980's and is predicted to continue well into the next century. This prediction is based on the observation of a stabilization of the world's capture fishery at around 100 million tons and an increasing demand for seafood as the world's population grows. Thus, production from aquaculture will have to expand to meet the increased market.

North America's contribution to world aquaculture accounted for slightly over 3% which pales in comparison to Asia's 87% contribution (Figure 1). Currently 13% of the seafood consumed in the United States is produced by the aquaculture industry. This percentage is forecast to double over the next ten years. Aquaculture production reached 715 million tons in 1994 for a value of $809 million. Catfish, rainbow trout and salmon were the leading farmed species.

Gulf of Maine Trends

Aquaculture within the Gulf of Maine was worth over $146 million (U.S.) in 1995, up from $112 million in 1992. Aquaculture production in the Bay of Fundy (New Brunswick) led the way in 1995 ($81 million), followed by Maine ($55 million), Massachusetts ($8.6 million) and New Hampshire ($810,000.) (Figure 2).

The dominant species in New Brunswick and Maine are Atlantic salmon and steelhead. The dominant species in New Hampshire and Massachusetts are trout and Northern Quahog, respectively. Other species of commercial importance are rainbow trout, Eastern oyster, hybrid striped bass, nori, baitfish, scallops and mussels.

In Maine and the Bay of Fundy, which are the two largest aquaculture producing areas within the Gulf of Maine, finfish production has increased steadily over the past 8 years. In Maine, production has increased from 450 metric tons produced from ten sites in 1988, about 10,000 metric tons of salmonids produced at twenty-five sites in 1995 (Figure 3). In the Bay of Fundy, production has increased from over 2800 metric tons produced at thirty-six farms in 1988, to over 14,000 metric tons from seventy-one farms in 1995 (Figure 3). The Bay of Fundy figures represent production for Atlantic salmon and rainbow trout. In Maine, the industry is more diverse, with shellfish and aquatic plants being produced as well.

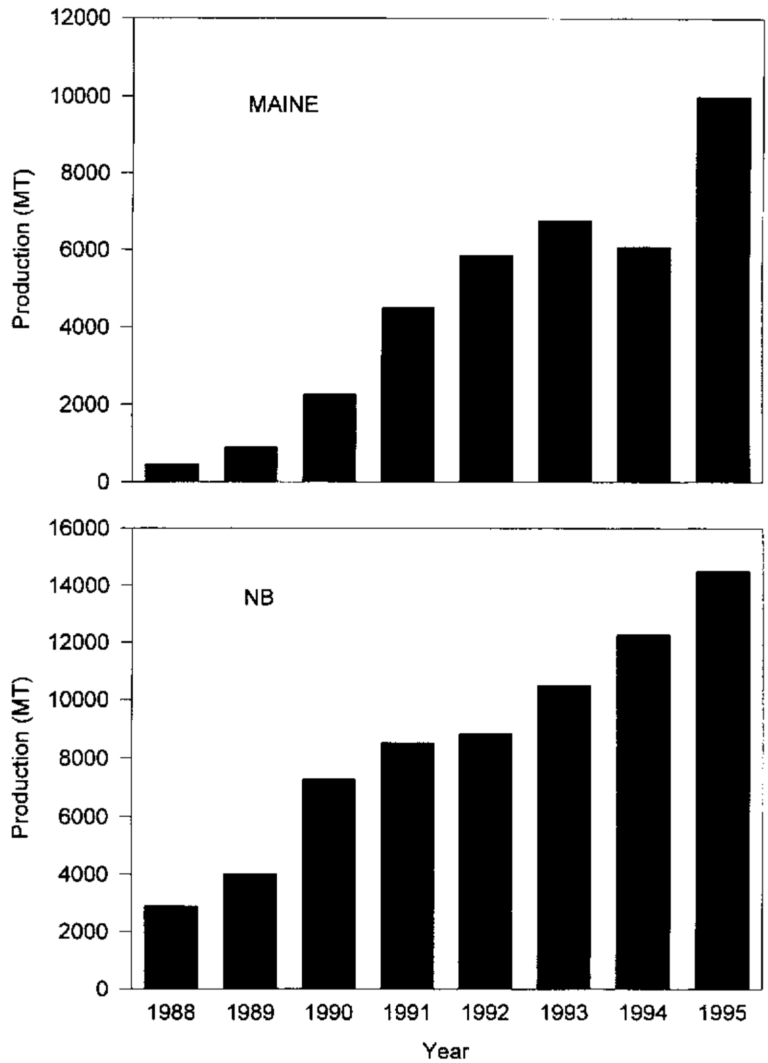


Figure 3. Salmonid aquaculture production in metric tons for Maine and New Brunswick over the period 1988 - 1995.

The value and production of shellfish and aquatic plants in Maine is also increasing. Farm raised mussels (*Mytilus edulis*) in Maine had a value of over one million dollars (U.S.) in 1995. Typically mussels are seeded on the sea floor and then harvested a couple of years later with a bottom drag. This is also the method of choice for growing American oysters (*Crassostrea virginica*). Bottom seeding is also carried out with soft-shell clams (*Mya arenaria*) with juveniles produced from hatchery seed. The expectation is that these species will enjoy increased production over the next five years.

Nori (*Porphyra yezoensis*), a red algae, is Maine's newest aquaculture product. It is a seaweed and is one of the essential ingredients of sushi. Currently Maine has the only Nori processing plant in the western hemisphere.

Aquaculture production in Massachusetts is driven primarily by Northern quahog/hard clam (*Mercenaria mercenaria*) and American oysters. Production over the past three years has varied but expectations are that the value and production of these species will continue to increase. Trout, striped bass and scallops are other contributing species. New Hampshire has the smallest aquaculture production within the Gulf of Maine which is primarily driven by trout production. Production of trout in New Hampshire has increased over the past three years and expectations are that production will continue to increase.

In spite of the strong position and future potential for growth of aquaculture in the Gulf, there are three major constraints for the industry. In a recent report on Aquaculture in the Northeast United States (Spatz et al. 1996), government regulation, predation, and financial capital were identified as the top three constraints to aquaculture in 1995; the same three topped the list in 1992. Regulation was the top constraint, followed by predation, and access to financial capital.

Development of New Species

With the dramatic collapse of the groundfish stocks in the Gulf of Maine, interest in developing new species for aquaculture has emerged. There are many reasons for developing new candidate species for aquaculture. These have been recently outlined for the Atlantic Region of Canada (Brown et al. 1995) and many of the reasons are similar for the Gulf of Maine. Prime among these are to broaden the base of aquaculture in the region, to develop new products for a growing market, and to provide job opportunities. As mentioned, most of the aquaculture production in the region is from salmonids, blue mussel and American oyster. The decline and closure of entire sectors of the harvest fishery in the region has resulted in greater attention being paid to expanding efforts in aquaculture to include new species. Hence, interest in diversification is, in part, being fueled by the possibility of identifying new sources of profit from an expanded aquaculture industry.

Tilseth (1990), in a review on the possibilities of aquaculture of new finfish species in Norway, stressed the importance of paying particular attention to market value, cost of production and quality of the product before considering the development of a new product. These factors are likewise important for shellfish and are indeed valid factors to be considered when assessing the potential suitability of any species. However, the biological perspective must also receive special attention (Brown et al. 1995). The species chosen for development can only present a reasonable market and production outlook if they are suited for the geography and climate in which they are grown. However, marketing and biological considerations are interdependent, since biological suitability influences production costs and increased output.

The reasons and criteria for developing new species are straightforward. Unfortunately, the time frame from initiation of research to the commercialization of the product can be extensive. For example, research on turbot (*Scophthalmus maximus*), sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) began in the early 1970s and by 1986 approximately 5.9 million juveniles were being produced, largely by countries bordering the Mediterranean Sea (Sweetman 1992). By 1995, these levels increased to over 30,000 tons for bass and bream. It is expected that in 1996 the production will increase 34%, to over 40,000 tons (*World Aquaculture,* 27(2) 1996)

Thus, in general, it takes ten to fifteen years from initialization of research to commercial production. However, the time frame can be considerably reduced if technology and expertise has been developed elsewhere and can be exported and modified to meet local conditions. Two examples of this in the Gulf of Maine are Atlantic halibut (*Hippoglossus hippoglossus*) and Atlantic cod (*Gadus morhua*). Initial work on culturing these two species has recently begun in New Brunswick and Maine.

The technology and knowledge for culturing halibut and cod has been developed in Norway (see Brown et al. 1995 for review). Halibut aquaculture research started in Norway in the late 1970s and continued through the early 1990s. Today commercialization of this species has started in Norway, and a commercial operation has completed its first production season in New Brunswick. Halibut is a very valuable species and is likely to retain its high value through the first years of commercialization. This is because existing sales are low due to limited supply from the harvest fishery. Markets can be easily expanded and will provide good profits to those first in the market. Cod aquaculture began in the late 1800s in Norway and was actively pursued until the 1990s. The situation in Norway changed because markets for cultured cod product were not strong due to the large wild fishery. Currently in Newfoundland, a commercial cod hatchery has just completed a successful first year. Much of the knowledge and technology for this hatchery was based on the Norwegian experience. The Newfoundland hatchery was started because of the moratorium that shut down the wild fishery for cod and eliminated the source of cod used by the company for "ongrowing" (see Brown et al. 1995 for details). Thus, a hatchery had to be built which would provide cod for the fresh market. The difference between the Newfoundland and the Norwegian approach was that the cod from Newfoundland were to be "niche" marketed as fresh cod during the winter months when supplies were low and a premium price could be obtained. The success of this approach is yet to be determined but first year production was sufficient and, if a two year production cycle (egg to table) is achieved, the approach will likely be profitable. Interest in cod aquaculture in Maine is for enhancement and will be discussed later.

Other new species with much less of a history are also being pursued in the Gulf of Maine. In New Brunswick, haddock (*Melanogrammus americanus*), winter flounder (*Pleuronectec americanus*), yellowtail flounder (*Limanda ferruginea*) and striped bass (*Morone saxatilis*) are being examined in addition to halibut. Striped bass has been commercialized in Massachusetts but not in New Brunswick. On the shellfish side, scallops, both sea (*Pecten magellanicus*) and bay (*Argopecten irradians*) are being developed.

In Maine, in addition to the effort on cod (discussed later) and halibut, other new species being developed are haddock, sea scallops and surf clams (*Spisula solidissima*). Hatcheries are in place for cod, scallops and surf clams. In New Hampshire, efforts are underway on the feasibility of culturing summer flounder (*Paralichthys dentatus*) winter flounder, witch flounder (*Glyptocephalus cynoglossus*), the pen culture of cod, some seaweeds and scallops. Currently in New Hampshire, there is one commercial hatchery for summer flounder which has successfully produced juveniles. Efforts in Massachusetts mirror those in New Hampshire somewhat, with current finfish efforts focusing on cod for pen culture, haddock and summer flounder. There is interest by some commercial fishing companies in Massachusetts to make the transition to aquaculture and they are involved in pilot scale hatchery projects.

All of the above species have attributes necessary for the development of a new species. The species are regionally adapted and all have a history in the market. In some cases the current market value, based on wild catch, is low. However, historically, cultured products have commanded a higher price in the market than their wild-caught counter-parts. This is mainly due to the fact that the butchering of cultured products is better controlled, resulting in a higher quality product, and the cultured products are brought to the market fresh. This increased quality results in premium prices being paid.

Enhancement

As mentioned previously, the cod culture effort in Maine is directed toward enhancement of the depleted cod stocks. In 1993, the Maine State Legislature created the Groundfish Hatchery Study to investigate the economic feasibility of stock enhancement. Based on economic models which balanced the costs of hatchery operations against the income from a an enhanced fishery, two hatcheries began operation in 1995. The hatcheries will attempt to empirically test the assumptions of the models. A non-profit corporation was created to coordinate hatchery production efforts and to oversee the enhancement experiments. An additional component to this model was an effort to reestablish previously productive spawning/nursery areas along the coast of Maine. Much thought went into these enhancement efforts and a brief review of previous enhancement efforts and approaches is worthwhile.

There has been an enormous amount of enhancement effort over the past one hundred years, primarily focused on various salmonid species in many coastal and inland water systems. The magnitude of these efforts over the past fifty years are staggering; 1354 introductions of 237 species into 140 countries (Welcomme 1988). Reviews of these efforts have recently been done by Cowx (1994) and Stickney (1994) thus I will not go into great detail regarding these efforts and refer the reader to the above accounts. However, a few points are worth noting. As Cowx (1994) points out, few stocking programs have been properly evaluated but the evidence suggests that stocking rarely leads to any long-term tangible benefit. This is apparently due to indiscriminate stocking without well-defined objectives or prior appraisal of the likelihood of success. However, after a review of the available literature, Cowx writes that "if stocking programs are designed and implemented to satisfy defined goals it should be possible to improve the success rate". If the objective is enhancement then it is important that the system to be enhanced is not limited or low due to natural fluctuations in production. Thus a main objective of enhancement is to maintain or improve stocks where production is low for reasons other then natural fluctuations. There is no evidence of which I am aware that suggests the current situation in Maine (or elsewhere) is due to low oceanic production, rather overfishing has been put forth as the primary cause. Thus it appears that the situation in Maine is appropriate for enhancement. Norwegian efforts over the past decade and before are also worth reviewing in this regard.

The rearing of cod in Norway began in the 1880s and in 1884 cod larvae were released to enhance the coastal areas of Norway. This continued for over eighty years and was discontinued in 1971. The effectiveness of the effort was debated over the years, with many feeling that cod enhancement was valuable, while others were more skeptical. The rearing of cod had met with mixed success up to the mid-1980s. Several attempts to rear cod had resulted in less than 10% survival past metamorphosis. In the mid-1980s, a significant improvement in results were obtained (Kvenseth and Oiestad 1984). Using the small enclosure technique, survival rates to metamorphosis of up to 50% were achieved and greater then 10% of the larvae have been transferred as juveniles.

At a recent meeting in Arendal, Norway (The Ranching of Cod and Other Marine Fish Species, June 1993: *Aqua & Fish. Man.* 1994, 25) the success of the enhancement program was reviewed. Briefly, the success of the program was mixed. A major concern was the possibility that the carrying capacity of some of the fjord systems had been reached by enhancing with cod greater then 2.5 cm in length (Blaxter 1994). Another concern was that it was expensive to produce these large cod and that other methods for enhancement should be considered. Suggestions included the use of smaller cod and releasing them into the coastal areas where advected food would be more readily available (Blaxter 1994). This was felt to be feasible for several reasons. First, with advancements in genetic, chemical (Bloom et al. 1994) and other methods of tagging (e.g., temperature), it is now possible to "tag" eggs or larvae prior to their release. The use of broodstock with unique, neutral DNA would produce eggs and larvae with this marker DNA, and would enable their identification years down the road. However, while genetic tagging is still expensive, using chemical or other methods to "etch" the otolith or other bony parts during the larval stage is less costly and would also enable the "enhanced" fish to be identified. This was the major problem in the earlier attempts at enhancing using the early life stages of cod, as there was no way to determine if the enhanced fish had survived and if they were contributing to the biomass. Another critical part of the problem is to release the enhanced fish in the right place. This is especially true for larvae and juveniles.

Mortality during the early life stages of marine fish larvae is extremely high but it is believed that survival is best when larval production "matches" plankton production (Cushing 1975). These matches appear to take place in certain areas. These areas are typically frontal zones which have been shown to contain concentrations of zooplankton several orders of magnitude higher then non-frontal zones (Fortier et al. 1992) or semi-permanent gyral circulations such as has been found on the Georges Bank (Davis 1984). Typically these gyral areas entrain fish larvae and are often in close proximity to spawning areas (Munk et al. 1995). In order for enhancement to succeed we must identify the time and place in which retention and productivity is high in the area of interest. In conjunction with the above, we need to be able to predict and manipulate spawning times in the broodstock to produce eggs at the correct time. Systems for collecting buoyant, fertilized cod eggs have been developed, as have methods for rearing cod larvae. Good success has been achieved in both Maine and Newfoundland. Thus, large numbers of eggs can be produced and with recent success at marking otoliths of cod during the latter egg stages, it appears that the release of large numbers of marked larvae is achievable. Other methods being explored are releasing juveniles in historic spawning/nursery areas and a new strategy being studied in Newfoundland termed "grow and release".

According to an economic model produced in Maine, the release of juveniles is less cost-effective then egg or larval release. As stated above the release of eggs or larvae is not a trivial task as efforts must be taken to ensure that they are placed in an appropriate spot. This will require surveys, etc., and is not inexpensive. Placing juveniles in areas which had historically been nursery areas might in the long run be more cost effective if some of these enhanced fish survive to reproduce in these area. Results from Norway indicate that released cod survived well and had a minor impact on other organisms within the area (Fossa et al. 1994). The percentage of released cod in the area ranged from < 1% the first year to over 80% the last two years.

Thus, in Norway, released juveniles survived and had little detectable impact on resident cod. The situation in Maine will have to be monitored, but it appears that a juvenile release could result in reestablishing a spawning stock in certain inshore areas.

The last enhancement option I will discuss is a "grow and release" strategy which is being examined in Newfoundland. This strategy depends on a source of young two to four year old cod. In Newfoundland, prior to the moratorium, undersized cod were bought from the inshore, cod-trap fisherman and placed in sea pens (Brown et al. 1995). These cod were then ongrown for three months, during which time they would double (sometimes triple) their initial weight before being harvested in December. It was observed in cod which had been overwintered in pens, that many produced gametes in the spring as four year old fish. Thus the constant feeding of the cod had increased their size to the point where they would spawn as younger fish compared to their wild counterparts. Researchers at Memorial University of Newfoundland began to examine this in detail and found that by ongrowing fish for a couple of seasons, potential fecundity (vitellogenic oocytes) was twice as high for cod fed for three growth seasons and two to four times higher for fish grown over four growth seasons compared to wild cod of the same size. (Wroblewski et al. 1997). Thus the strategy is to capture small cod from a bay, hold and feed them for a couple of growing seasons (within the same bay) and then release them with their enhanced fecundity. Other studies have found that the eggs from the pen cod are equal to the viability of wild eggs and the behavior of released pen cod is similar to wild cod (Wroblewski et al. 1996). Expectations would be that the released cod would spawn with or in the same aggregations as wild cod, and would increase the spawning biomass significantly and, in the long term, increase recruitment.

The three options outlined above have not been proven as of yet, but with careful monitoring and modification where necessary, a cost-effective method to increase cod biomass over the short or long term might be achievable. A recent success story has been the Japanese effort to enhance coastal food fish such as red seabream and Japanese flounder. Estimates of the contribution of "enhanced" fish to the flounder market ranged from 19 - 61% (Kitada et al. 1992). High percentages of enhanced flounder not only survived but made a significant contribution in the marketplace three years after release. The results of this study concluded that the stock enhancement program was economically profitable and should be continued (Kitada et al. 1992). Thus if enhancement is done correctly the potential for improving biomass is achievable.

Potential Impacts

In this section I will discuss the impacts of both enhancement and cage culture. Most of the work on impact has been done on salmon farming as this aspect of the aquaculture sector has the longest history. The impacts from salmon aquaculture have taken two forms to date: environmental and escapees. The impact from enhancement efforts has been reported from Norwegian experiments on cod and will be discussed first.

In 1993 a conference was held in Norway to review the results of enhancement efforts of cod and other marine fish species. A number of researchers presented the results of ten years of cod enhancement in Norway. It was reported that enhanced cod, within weeks of release, had similar feeding efficiencies and antipredator behavior as their wild counterparts (Blaxter 1994). Enhanced cod had similar growth rates and tended to remain in the same locality as the wild cod, and the released cod had only a minor impact on the other organisms in the area (Fossa et al. 1994). On the negative side, there was no evidence that enhanced cod increased the fishery even though during the first months after release they did augment the stock. It was also reported that the carrying capacity of certain areas had likely been exceeded through the release of cod, and care should be taken in this regard. Overall, the release of cod in coastal habitats in Norway did not appear to have a major impact on the wild cod but the effectiveness of the program is unclear.

With regard to the environmental impact of salmonid aquaculture, the areas of highest salmonid activity, the Bay of Fundy and Maine, have quite robust monitoring programs. The Environmental Management Plan in New Brunswick was initiated in 1991 and is now conducted by the salmon growers. In Maine the Aquaculture Monitoring Program was also initiated in 1991. Both programs rely on video taping the substrate under and around cages at least once per year (twice per year in Maine), and sediment and water samples are also required. Reports are filed with the appropriate State or Provincial Departments and if serious degradation is indicated, action is taken to reverse the trend. In general there has been little serious degradation found; 15% in New Brunswick (Thonney and Garnier 1993) and just under 10% in Maine (Heinig 1994). In Maine a trial was conducted to determine how long it would take for a degraded site to recover. Results indicated that the site recovered in a year. Thus, to date, the Monitoring Programs are doing well and the environmental impact of the salmonid industry is not as high as predicted prior to the program's implementation.

The final impact to be discussed is that of cultured salmon "escapees" on wild salmon. Again, much of the information on this type of impact comes from Norway where in some spawning populations the number of cultured fish exceed wild fish (Heggberget et al. 1993). In a review of the interactions between wild and cultured fish in Norway, Heggberget et al. (1993) stated that the most serious effects so far have been the introductions of parasites and diseases from the cultured fish to the wild. One of the most serious parasites infecting salmon in Norway is *Gyrodactylus salaris,* a monogean ectoparasite. Over the past two decades it has infected young salmon in many Norwegian rivers. How this parasite arrived in Norway is not known but current thought is that it was introduced from Swedish salmon hatcheries (Heggberget et al. 1993). Another disease, furunculosis, was found in Norway for the first time after some rainbow trout had been imported from Denmark. In 1985 the disease was found in salmon in farms after an import of smolts from Scotland.

Another serious impact of escapees on wild fish is genetic. This can be expressed as genetic loss resulting in a breakdown of adapted gene complexes. An example of genetic introgression was that between local and released stocks of brown trout in Northern Ireland and France. At the other extreme is the lack of any introgression when andromous Atlantic salmon were released into areas where non-andromous populations existed (Vuorinen and Berg 1989). It has also been documented from both field and laboratory studies that the survival and performance of escaped cultured fish is poorer then wild fish. However, it has also been documented, through comparisons of optic isomers of astaxanthin (pigment used in commercial salmon feed), that escaped females deposit fertilized eggs that survive until at least the alevin stage (Heggberget et al. 1993). Thus the genetic impact of escapees could be quite dramatic in some situations. The other impact of escapees on the spawning ground is the physical disturbance of nests caused by the late spawning activity of cultured females.

There are measures which may be put in place which could mitigate or reduce the severity of the above impacts. Land-based rearing is one remedy for the impact of escapees or environmental degradation but currently it is considered too expensive for salmon farming given the price of salmon in the market. However, it is likely that land-based systems, with some recirculation, will be used for marine finfish; thus, as this technology becomes more routine and cost-effective, its use for salmonid farming might become feasible. Using sterile stocks of fish in cages eliminates the genetic concerns of escapees but potential ecological or physical disturbance problems would still exist. Localization of culture operations may help protect natural populations. Locating farms 20 km or more from rivers where natural spawning occurs has been shown to reduce the impact in some Norwegian systems (Gausen and Moen 1991). It appears that environmental impact is less likely to be a major problem given the monitoring programs in place in certain areas. As other areas begin to increase cage culture operations, it is necessary that sound monitoring programs be put in place.

Conclusions

There is no doubt that aquaculture is an industry which is here to stay and will expand over the next decade and beyond. It will be a major user of the coastal zones in the Gulf of Maine and offshore operations are likely to be developed over the next decade. Aquaculture is a growing sector of the agrifoods industry and as such is not a fishery. This "jurisdictional" problem will need to be addressed in the future. It is an issue that has already been debated in Congress, and in the future, aquaculture will likely be considered agriculture as opposed to a "fishery".

One of the major constraints to aquaculture, as cited in a recent report, is overburdening government regulation. This needs to be addressed, but the industry needs to keep its environmental house in order as its share of the responsibility. In general this is done, as it is to the industry's advantage not to pollute its own nest. Environmental monitoring programs are in place in some areas and these need to be maintained. I would suggest that, if the wild fishery was monitored as closely for environmental impact as the aquaculture industry, the status and prosecution of the fishery today would be vastly different. The efficacy of programs for enhancement need to be closely monitored to determine their success. User conflicts are likely over the next years but, if the scientists do their job at providing good data, and the managers do a good job at ensuring that all groups are at the table when decisions are made, then conflicts should be resolvable.

References

Blaxter, J.H.S. 1994. Summary of symposium. *Aqua. & Fish. Man.*, 25:259-264.

Bloom, G., J.T. Nordeide, T. Svasand, and A. Borge. 1994. Application of two fluorescent chemicals, alizarin complexone and alizarin red S, to mark otoliths of Atlantic cod *Gadus morhua*. *Aqua. & Fish. Man.* 25:229-244.

Brown, J.A., M. Helm, and J. Moir. 1995. New candidate species for aquaculture. In *Cold-Water Aquaculture in Atlantic Canada*, ed. A.D. Boghen. 341-362.

Cowx, I.G. 1994. Stocking strategies. *Fish. Man. & Ecol.* 1:15-30.

Cushing, D.H. 1975. *Marine Ecology and Fisheries.* Cambridge: Cambridge University Press.

Davis, C. 1984. Interaction of a copepod population with the mean circulation on Georges Bank. *J. Mar. Res.* 42:573-590.

FAO. 1992. Fisheries Circular no. 815, Revision 4, FAO. Rome, June 1992

Fortier, L., M.E. Levasseur, R. Drolet, and J-C. Therriault. 1992. Export production and the distribution of fish larvae and their prey in a coastal jet frontal region. *Mar. Ecol. Prog. Ser.* 85:203-218.

Fossa, J.H., J.Y. Nordeide, A.G.V. Salvanes, and O.M. Smedstad. 1994. Impacts of mass released cod *Gadus morhua* L., on wild fish populations in Masfjorden, western Norway. *Aqua. & Fish. Man.* 25:35-48.

Gausen, D. and V. Moen. 1991. Large-scale escapes of Atlantic salmon, *Salmo salar*, into Norwegian rivers threaten natural populations. *Can. J. Fish Aquat. Sci.* 48:426-428.

Heggberget, T.G., B.O. Johnsen, K. Hindar, B. Jonsson, L.P. Hansen, N.A. Hvidsten, and A.J. Jensen. 1993. Interactions between wild and cultured Atlantic salmon: a review of the norwegian experience. *Fish. Res.* 18:123-146.

Hempel, E. 1993. Constraints and possibilities for developing aquaculture. *Aqua. Internat.* 1: 2-19.

Heinig, C. S. 1996. The Maine Department of Marine Resources Finfish Aquaculture Monitoring Program (FAMP) 1992-1995. Maine Dept. Mar. Res. Report.

Kitada, S., Y. Taga, and H. Kishino. 1992. Effectiveness of a stock enhancement program evaluated by a two-stage sampling survey of commercial landings. *Can. J. Fish. Aquat. Sci.* 49: 1573-1582.

Kvenseth, P.G. and V. Oiestad. 1984. Large-scale rearing of cod fry on the natural food production in an enclosed pond. In *The Propopagation of Cod (Gadus morhua L.)* eds. E. Dahl, D.S. Danielssend, E. Mockness, and P. Solemdal. Flodevigen rapportser Oluf Rasmussen, A.S., Skien.

Munk, P., P.O. Larsson, D. Danielsen, and E. Moksness. 1995. Larval and small juvenile cod *Gadus morhua* concentrated in the highly productive areas of a shelf break front. *Mar. Ecol. Prog. Ser.* 125:21-30.

Spatz, M.J., J.L. Anderson, and S. Jancart. 1996. *Northeast Region Aquaculture Industry Situation and Outlook Report*. Rhode Island Experimental Station Pub. No. 3352.

Stickney, R.R. 1994. Use of hatchery fish in enhancement programs. *Fisheries.* 19:6-13.

Sweetman, J. W. 1992. Larviculture of Mediterranean marine fish species: Current status and future trends. *J. World Aqua. Soc.* 23:330-337.

Thonney, J-P. and E. Garnier. 1993. Bay of Fundy Salmon Aquaculture Monitoring Program, 1992 - 1993. *N.B. Dept. of Environ. Report.* 22 pp.

Tilseth, S. 1990. New marine species for cold-water farming. *Aquaculture* 85:235-245.

Welcomme, R. L. 1988. International introductions of inland aquatic species. FAO Fisheries Technical Paper 294.

Vuorinen, J. and O.K. Berg. 1989. Genetic divergence of anadromous and nonandromous Atlantic salmon Salmo salar in the River Namsen, Norway. *Can. J. Fish. Aquat. Sci.* 46:406-409.

Wroblewski, J.S., H.W. Hiscock, and I.R. Bradury. 1997. Fecundity of Atlantic cod *Gadus morhua* farmed for stock enhancement in Newfoundland bays. *J. Fish Bio.* (in press).

Wroblewski, J.S., R.K. Smedbol, C.T. Taggart, and S. Goddard. 1996. Movements of farmed and wild Atlantic cod *Gadus morhua* released in Trinity Bay, Newfoundland. *Mar. Biol.* 124:619-627.

Working Group Reports

Recent Research Results

The following people were asked to discuss the results of their research in the context of the broad questions being addressed by the meeting to stimulate discussion in the various working groups. The presentations were not intended to summarize individual research activity, but rather, were envisioned as a presentation of ideas that had broader research implications for all who are engaged in Gulf of Maine research. Each speaker was given five minutes to present speculative ideas that would stimulate the working group discussions that followed in the program. The researchers are listed below with their poster presentation title (see Poster Session Abstracts in this volume), under the designated working group session topic.

Physical and Biological Coupling in the Gulf of Maine

David Brooks, *Modeling the Circulation in Cobscook Bay*

James Churchill, *Response of Georges Bank Waters and Larvae to the Passage of a Gulf Stream Warm-Core Ring*

Edward Durbin, *Dynamics of Calanus Finmarchicus on Georges Bank During 1995*

Rocky Geyer, *Vertical Mixing in Massachusetts Bay*

Charles Hannah, *The Role of the Surface Ekman Layer in the Calanus Supply to Georges Bank*

Land /Water Interface: Biogeochemical Cycles, Natural and Perturbed

Michael Bothner, *The Decrease of Metal Concentrations in Surface Sediments of Boston Harbor*

Robert Chen, *Continuous Fluorescence Measurements for High Temporal and Spatial Resolution of Organic Compounds in Marine Systems*

Ted Loder, *Spring Pulse and Annual Nutrient Input by the Kennebec River to the Western Gulf of Maine Coastal Zone*

Cynthia Pilskaln, *Particulate Flux Dynamics in Jordan and Wilkinson Basins: Seasonal POC Export and Particle Resuspension*

Fishery & Aquaculture Issues

Ted Ames, *Current Efforts to Enhance Cod Stocks in the Gulf of Maine*

Lewis Incze, *Relationship Between Postlarval Supply and Benthic Recruitment of Lobsters in the Western Gulf of Maine*

Rodney Rountree, *Diet of Key Fishes Collected in the Gulf of Maine During NEFSC Bottom Trawl Surveys Conducted from 1981-90*

Daniel Schick, *Seasonal Distribution of Finfish in the Coastal Western Gulf of Maine Relative to Bottom Water Temperatures, Sediment Grain Size, Sediment Carbon and Nitrogen levels, and the Fishery for Northern Shrimp*

Susan Waddy, *Is "Real Time" the Key to Understanding how Temperature Influences Recruitment in the American Lobster?*

Human Induced Biological Changes

Mark Chandler, *Differences in Fish Communities Among Nearshore Habitats in Boston Harbor and Northern Massachusetts Bay*

Michael Connor, *Predicted Impacts of MWRA's Discharge to the Mass Bay System: Environmental Monitoring Changes the Problem Definition*

Michael Moore, *Organic Chemical Contaminants in Gulf of Maine Plankton and a Biomarker of their Circulation in the Zooplanktivorous Right Whale*

Page Valentine, *New Imagery of Seabed Environments in the Stellwagon Bank Region, Gulf of Maine*

Physical/Biological Coupling

Robert Beardsley
Woods Hole Oceanographic Institute, and
Bradford Butman
United States Geological Survey

Working Group Members:

Eric Adams, Massachusetts Institute of Technology
Job Baretta, Danish Hydraulics Institute
Robert C. Beardsley, Woods Hole Oceanographic Institution
Bruce Bourque, Bates College
David Brooks, Texas A & M University
Wendell Brown, University of New Hampshire
Frank Bub, University of New Hampshire
Donna Busch, National Marine Fisheries Service
Bradford Butman, U.S. Geological Survey
Janet Campbell, University of New Hampshire
Maria Casas, University of Rhode Island
Fei Chai, University of Maine
James Churchill, Woods Hole Oceanographic Institution
Edward Durbin, University of Rhode Island
Derek Fong, Woods Hole Oceanographic Institution
Paul Fucile, Woods Hole Oceanographic Institution
George Gardner, University of Massachusetts at Boston
Karen Garrison, University of New Hampshire
Wendy Gentleman, Dartmouth College
W. Rockwell Geyer, Woods Hole Oceanographic Institution
John Green, National Marine Fisheries Service
Charles Hannah, Oceadyne Environmental Consultants
Erica Head, Department of Fisheries and Oceans Canada
Eileen Hofmann, Old Dominion University
Monica Holboke, Dartmouth College
Lewis Incze, Bigelow Laboratory for Ocean Sciences
Frank Johns, TAS Editorial Services
Ronald Loucks, Loucks Oceanology Ltd.
R. Gregory Lough, National Marine Fisheries Service
James Manning, National Marine Fisheries Service
Jennifer Martin, Department of Fisheries and Oceans Canada
Dennis McGillicuddy, Woods Hole Oceanographic Institution
Dorothy Medeiros-Bergen, University of New Hampshire
Christopher Naimie, Dartmouth College
Fred Page, Department of Fisheries and Oceans Canada
Richard Peterson, Department of Fisheries and Oceans Canada
Neal Pettigrew, University of Maine
Jeffrey Proehl, Dartmouth College
Ronald Schlitz, National Marine Fisheries Service
Nancy Shackell, Dalhousie University
Richard Signell, U.S. Geological Survey
William Silvert, Department of Fisheries and Oceans Canada
Peter Smith, Department of Fisheries and Oceans Canada
Andrew Thomas, University of Maine
Lou Van Guelpen, Huntsman Marine Science Centre
Francisco Werner, University of North Carolina
Sandra Werner, Woods Hole Oceanographic Institution
David Wildish, Department of Fisheries and Oceans Canada
William Williams, Woods Hole Oceanographic Institution
Huijue Xue, University of Maine
Charles Yentsch, Bigelow Laboratory for Ocean Sciences
Yi Xian Zhang, University of Massachusetts at Boston

Summary

The Physical/Biological Coupling Working Group identified three broad areas where improved scientific knowledge of coupled physical/biological processes is needed to better understand the natural environment and separate human-induced impacts from natural variability: (a) estuarine/nearshore/gulf/slope exchange, (b) benthic/pelagic coupling, and (c) life cycles and physical processes.

The Physical/Biological Coupling Working Group recommends a science initiative to investigate the Gulf of Maine coastal current(s). The coastal current occupies a broad band from the coast to perhaps 50 km offshore, and provides a pathway by which nutrients, contaminants and organisms are distributed throughout the Gulf of Maine. The coastal current occupies the

Table 1.
Summary of Scientific Issues Considered by Physical / Biological Coupling Working Group

Categories of human activity which potentially impact the health of the Gulf of Maine ecosystem:
- Loadings (natural and anthropogenic): point and non-point nutrient sources including terrestrial management, natural freshwater variability and management.
- Resource Management: submerged aquatic vegetation, fisheries (pelagic, benthic, near-shore, open-gulf), enhancement, aquaculture, marine mammals.
- Anthropogenic Habitat Alteration: restoration, dredging, sand and gravel mining, offshore drilling, bottom fishing, aquaculture.
- Climate Change: sea-level rise, temperature, precipitation, wind, changes in subpolar supply.

Potential biological consequences of these activities:
- Primary productivity (eutrophication/low DO, harmful algal blooms)
- Secondary productivity (fish populations)
- Biological distributions
- Habitat degradation (spawning, benthic fish)
- Biodiversity and aquatic health vs. human health

Principal Physical/Biological Processes which need to be understood in order to understand the natural environment and separate the human-induced impacts from natural variability:
- Estuarine/Nearshore/Gulf/Slope Exchange
- Benthic/Pelagic Coupling
- Life Cycles and Physical Processes

Cross-cutting Issues:
- Model development needed for prediction
- Monitoring needed to detect trends and support model efforts
- Information (data exchange, archives, etc.)
- Technology
- Mechanisms to facilitate effective science/management interaction
- Science Initiatives

region where there is intense anthropogenic activity (waste disposal, dredging, over fishing, etc.) and where remediation of anthropogenic effects are beginning. Such an initiative would provide the opportunity to carry out a coordinated research program that addresses fundamental scientific issues in the broad areas of exchange, benthic-pelagic coupling, and life cycles (see sub-group reports for detail), and simultaneously provide information of direct use for near shore management. Key research topics that could be addressed as part of a Coastal Current(s) Initiative include:
- Occurrence and causes of harmful algal blooms
- Ecology of larval cod, especially in relation to inshore historical spawning grounds
- Mixing between estuarine, coastal current, and interior of the Gulf of Maine
- Effects of bottom trawling on benthic habitat

The Gulf of Maine coastal current system plays an important role in the physics and biology of these issues. The proposed initiative would focus a suite of topical scientific studies to enhance understanding of physical/biological coupling and of this complex and important system. The study should be undertaken as soon as possible in order to take advantage of present major research programs like the U.S. GLOBEC/Georges Bank Program study to provide simultaneous gulf-wide measurements.

Introduction

The Physical/Biological Coupling Working Group met in the morning first in plenary session to discuss the central charge to the working group and develop a set of scientific objectives or issues based on the initial panel discussion of management issues facing resource managers in the Gulf of Maine. After considerable group discussion, this working group broke into four subgroups chaired by W. Brown and J. Baretta, B. Butman, R. Geyer, and L. Incze. The principal charge was to outline some of the principal issues in Physical / Biological coupling. After lunch, the working group again met in plenary session to listen to the results of the morning subgroup discussions which were then distilled into the summary shown in Table 1.

Table 2.
Key research topics that could be addressed as part of the "Gulf of Maine Coastal Currents" initiative recommended by the Physical/Biological Coupling Working Group

The Gulf of Maine coastal current system plays an important role in the physics and biology of these issues. The proposed initiative would focus a suite of topical scientific studies to enhance understanding of physical/biological coupling of this complex and important system.
1. Occurrence and causes of harmful algal blooms
2. Ecology of larval cod, especially in relation to inshore historical spawning grounds
3. Mixing between estuarine, coastal current, and interior of the Gulf of Maine
4. Effects of bottom trawling on benthic habitat
5. Transport and fate of contaminants
6. Effects of inshore salmon farming and traditional fishing methods on near shore and offshore environments
7. Effects of internal waves on mixing and suspended sediments
8. Role of benthic communities in structuring plankton communities and vice-versa
9. Benthic regeneration of nutrients
10. Relative importance of Gulf vs. Riverine sources of nutrients

The working group then broke into three subgroups to discuss in detail the state of present understanding of the key physical and biological processes listed above as (a) estuarine/nearshore/Gulf/Slope exchange, (b) benthic/pelagic coupling, and (c) life cycles and physical processes. The subgroups also identified possible research initiatives needed to improve scientific understanding and help resolve management issues. Oral reports were given in plenary session the next day by the subgroup chairmen, who then prepared the following written reports. Key scientific issues identified by the subgroups are summarized in Table 2.

Estuarine/Nearshore/Gulf/Slope Exchange

Physical/Biological Coupling Between the Nearshore and Offshore: Multiscale Interactions Across the Gulf of Maine Coastal Current

Rocky Geyer

Introduction

Some of the most urgent environmental problems of the Gulf of Maine involve the nearshore environments such as estuaries and harbors around the perimeter of the Gulf. These include accumulation of toxic compounds in sediments, eutrophication, loss of habitat, the impacts of harmful algal blooms, shoreline erosion, siltation and dredging, aquaculture, and coastal fisheries resources. The physical and biological processes within these nearshore environments depend sensitively on larger scale processes within the Gulf of Maine. The strong tides in the Gulf provide an important agent of exchange between individual harbors and the Gulf, and the Gulf of Maine Coastal Current (Beardsley et al., this volume) provides a conduit between different nearshore environments along the coast, and potentially between the coastal zone and the interior of the Gulf. Coupling between nearshore environments and offshore waters is important in all coastal environments, but the particular physical characteristics of the Gulf of Maine (e.g., its strong tides, steep bathymetry, and energetic coastal current) make these coupling processes even more important.

This chapter identifies several important, interdisciplinary, research themes that involve the coupling between the nearshore and the offshore portions of the Gulf of Maine. In order to address effectively these research problems, we must adopt a multi-scale approach, which encompasses the full range from Gulf-scale transport processes to the local physical/biological interactions within an embayment. Undertaking a research project that encompasses such a broad range of scales demands new approaches, on the one hand to the observations, analysis and modeling, and on the other hand to the sponsorship and management of the scientific research. The recent advances in numerical modeling in general and in the Gulf of Maine in particular provide a computational structure to couple processes at the Gulf-wide scale with local conditions within an embayment. We must also look toward a partnership between local, national and international funding sources to support the research activities that extend across different scales and different jurisdictional boundaries.

Multi-scale Environmental Issues in the Gulf of Maine

Nutrients: What is relative importance of Gulf sources vs. riverine sources – acute vs. large-scale effects?

Harmful Algal Blooms: What is the role of different source populations on blooms, and the importance of coupling between the embayments of east Casco Bay and the coastal current zone in timing and spread of blooms?

Transport and Fate of Contaminants: What are the fates of particle-reactive compounds and other contaminants being carried through the coastal harbors and embayments into the coastal current?

Fisheries: What is the effect of inshore salmon farming and cod fishing, on the nearshore and offshore environments?

Research Topics

Effects of coastal current on estuarine exchange.

Exchange between coastal current and interior – existence of branch points along coast.

Coupling of geochemistry and physics – identifying relevant scales, approaches.

Coupling of biology and physics.

Approach

Multi-scale investigations, near-field, far-field studies, multi-scale modeling.

Coupled models – varying complexity, physics – geochemistry – biology.

Numerical simulations leading toward prediction.

Multiple Funding Sources.

Benthic-Pelagic Coupling and Exchange

J. Churchill and E. Durbin

Introduction

The Gulf of Maine environment is strongly influenced by coupling between the benthic and pelagic zones. The exchange between these zones is critical to maintaining the food and nutrient supply of both benthic and pelagic communities. Sinking organic particles are a primary source of nourishment to benthic communities. When incorporated into bottom sediments, these become a repository of nutrients which can fuel pelagic production if reintroduced to the euphotic zone. The fate of contaminants within the Gulf of Maine, which are largely bound to small particles, is also strongly linked to benthic-pelagic exchange.

Benthic-pelagic coupling is subject to both biological and physical influences. For example, various physical processes effect sediment resuspension and vertical sediment movement. Benthic organisms also influence particle dynamics by removing particles through feeding; a process which can actively structure planktonic communities. Excretion of nutrients in ingested material by benthic organisms and remineralization of nutrients can fuel pelagic production by phytoplankton.

Our working group identified four types of processes which effect and/or influence benthic-pelagic exchange. Here we briefly review their operation and discuss what we consider to be the most critical deficiencies in our understanding of these processes.

Physical Processes Influence Benthic-Pelagic Exchange

The Action of Currents

The Gulf of Maine, like all coastal seas, is subject to a wide range of current types (e.g., wind-driven flows, surface wave currents, tides, etc.), each with its own scale and generation mechanisms. Acting in various combinations, these can effect benthic-pelagic exchange by exerting stress on and resuspending bottom particles, and carrying and/or mixing material vertically through the water column. While the understanding of all of these current types is imperfect, our group singled out two which we deemed to be both poorly studied and of potential great importance to benthic-pelagic exchange within the Gulf of Maine. One is internal waves. Locally, internal waves can significantly contribute to bottom stress generation and sediment resuspension. The Gulf of Maine has ingredients for generation of vigorous internal waves: stratification, strong tidal and wind-driven flows, and irregular bathymetry. Yet little is known of the distribution of internal wave energy within the Gulf, or of the details of the generation of internal waves and their effect on bottom sediments of the Gulf. The other current type we deemed in particular need of study is the vertical motions at fronts. It is well established that coastal fronts are high areas

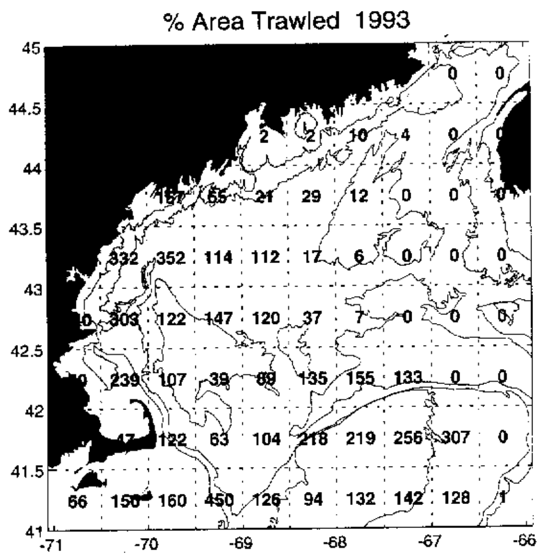


Figure 1. Estimated distribution of the area covered by bottom trawls during 1993. The number shown within each box is an estimate of the ratio, in percent, of the cumulative area covered by trawl gear within the box during 1993 to the total box area. Estimates of area trawled were obtained by multiplying the total time of bottom trawling, obtained from National Marine Fisheries Service records, by a representative width and over-ground speed of trawl gear.

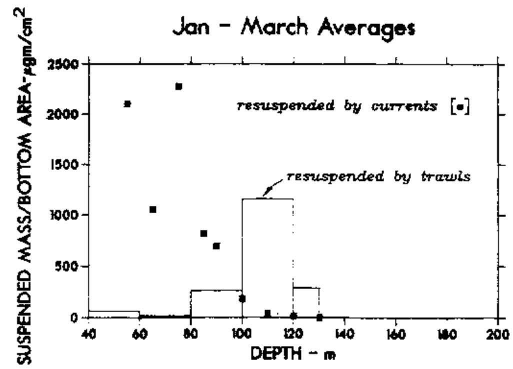


Figure 2. A comparison of the estimated mean sediment load put into suspension by currents (boxes) and bottom trawls (histogram) over the shelf south of Cape Cod. Estimates of current resuspended sediment load were computed using current meter data and a modified form of a model developed by Glenn and Grant (1987). Estimates of the trawl resuspended sediment load were determined with National Marine Fisheries Service records of trawling activity and a model developed by Churchill (1989).

of high productivity, owing in part to vertical motions at frontal boundaries. However, little is known about how currents tied to fronts within the Gulf of Maine interact with bottom material and benthic communities.

Our group also noted that fluid and particle dynamics of the bottom boundary layer within the Gulf of Maine have been given very little scientific attention. Understanding and modeling particulate movement within the Gulf requires an ability to quantify various processes and properties within the bottom boundary layer. In particular need of study are: how the stress threshold for sediment resuspension varies temporally and with sediment type, how stress generation during storms is influenced by evolving bottom bedform features, and how vertical stratification (due to gradients in water properties and suspended sediment concentrations) influences bottom stress generation and vertical particle motions.

Our group concluded that a regional or local study of flows within the Gulf should include an investigation of the effects of internal waves, vertical motions and exchange at fronts and fluid and particle dynamics within the bottom boundary layer.

Bottom Fishing

In addition to currents, a physical mechanism which can effect benthic-pelagic exchange and significantly alter the benthic environment is the action of bottom fishing gear. The Gulf of Maine, and most other areas off the United States East Coast, are subject to intensive bottom fishing, principally trawling and dredging. Some areas of the Gulf are traversed by fishing gear a number of times during the course of a year (Figure 1). The few studies of effects of trawls on sediments have shown that trawling can resuspend tremendous quantities bottom material, producing plumes with suspended solids concentrations in excess of 0.5 gm/l. Results of a modeling study indicate that trawling may be the principal mechanism responsible for resuspending sediments over some areas of the outer shelf (Figure 2). A meaningful assessment of the role of trawling on sediment dynamics of the Gulf of Maine will require more quantitative measures of the properties of trawl-induced plumes than currently available. Properties which must be quantified to accurately model the transport of trawl-resuspended material include: the rate (mass per unit time) at which individual trawls resuspend material, and the initial height and the settling time of the trawl-induced sediment plume.

Another issue of concern is the effect of bottom fishing on the benthic habitat. Only recently has this been a subject of scientific study. Current work suggests that the impact of bottom fishing on the benthic environment may be greatest in deeper areas not subject to frequent episodes of resuspension due to currents. However, present knowledge is deficient regarding the effects of bottom fishing on individual species, or how long-term fishing of a region may alter benthic species composition.

Biological Processes Affect Benthic-Pelagic Coupling

The Action of Benthic Suspension Feeders

There are a number of benthic organisms which are suspension feeders actively removing particles from the water column. These include animals which feed on smaller phytoplankton-sized particles (e.g., mussels, clams, scallops), others which feed on zooplankton (e.g., hydroids, mud anenomes), and some which feed on both (e.g., amphipods). The role of benthic communities as predators on planktonic organisms and in structuring pelagic food webs was recently reviewed by Sullivan et al. (1991). In the Bay of Fundy, extensive mussel beds appear to significantly affect phytoplankton concentrations. This process has received little attention elsewhere in the Gulf of Maine - Georges Bank region. Because of the extensive inshore shallow areas and offshore banks, and the strong tidal currents and associated high mixing rates which increase the encounter rate of planktonic organisms with these benthic predators, it was concluded that this process is likely to be important in the Gulf of Maine-Georges Bank region. The working group noted that the ongoing U.S. GLOBEC study of Georges Bank investigating biophysical interactions within the plankton does not include this potentially important component. It was recommended that the role of benthic organisms in structuring plankton communities should be further investigated.

Regeneration of Nutrients from the Benthos

Regeneration of nutrients from the benthos is an important process in fueling phytoplankton communities in shallow regions. Regeneration of nutrients may occur through excretion by benthic organisms and through remineralization by bacteria. The significance of this process is greatest during the summer since it is strongly temperature dependent. Also, nutrients from the winter are largely used up by this time. In shallow regions, such as Narragansett Bay, benthic regeneration is entirely responsible for supporting phytoplankton production during the summer. At present, there is little information on the role of benthic regeneration in supplying nutrients to phytoplankton in regions such as Georges Bank or the Bay of Fundy. Our working group recommended that this area receive further study.

Life Cycles and Physical Processes

Lew Incze

Introduction

The larger working group concluded that a focus on the coastal zone would be valuable from both scientific and management perspectives. The subgroup on Life Cycles and Physical Processes considered how ongoing work and new initiatives in our subject area might fit into a general theme that included near-coastal processes as well as linkages with larger-scale features of the Gulf of Maine. We were concerned that physical and biological exchanges with the larger Gulf of Maine be addressed explicitly. We were concerned, as well, that the product of this working group would be of interest on both sides of the U.S.-Canadian border.

Points of Discussion

As a strategy, we approached our topic first from the viewpoint of various trophic levels. We did not go through the entire list of possibilities, recognizing that we did not have all the needed expertise within the group; however, we wanted to make certain that identified areas of focus were not meant to be exclusive. We felt that our recommendations should be specific enough to stimulate new initiatives but roomy enough to accommodate new ideas.

Second, we searched for logical extensions of ongoing efforts. We quickly identified harmful algal blooms as one topic in need of geographical expansion and a better understanding of occurrences and mechanisms. For example, much of the recent work on toxic dinoflagellate blooms (see abstract by Signell et al., this volume) and *Phaeocystis* spp. (abstract by Keller and Haugen, this volume) focus on the western Gulf. Another obvious extension of ongoing work concerns the ecology of cod. There is extensive work being done on this species as part of the Cod and Climate Change, GLOBEC and OPEN programs and there is growing interest in reestablishing a coastal cod fishery. The work presented by Ames at this meeting (see abstract, this volume) shows a large number of historical coastal spawning grounds, but we know little about what made these grounds successful for cod or whether or not this would still be true. There are, as well, fundamental questions about larval survival and transport and juvenile life history: is the knowledge gained from Georges Bank applicable to the nearshore environment? There also are questions about higher trophic level interactions (see plenary paper by Steneck, this volume). In short, studies of harmful algal blooms and of cod involve broad areas of work in nutrients, ocean physics, primary and secondary production, fisheries and higher trophic levels.

Third, we considered how the above topics might be worked into a programmatic theme that would include: (1) some of the other processes we were not covering ourselves (e.g., estuarine inputs, exchange with the Gulf of Maine; and (2) a synergism between Canadian and U.S. work. This brought us rather quickly to a geographic recommendation focusing on the northwestern Gulf of Maine with the following elements: Scotian Shelf inflow and Eastern Maine Coastal Current, Jordan Basin, Bay of Fundy and Penobscot Bay. Both of the bays are large features with significant riverine input, complex ecological systems and large exchanges with neighboring "offshore" waters. The Scotian Shelf inflow is a major source of Gulf of Maine surface water and forms a continuum with the Eastern Maine Coastal Current (EMCC), although the latter arises from distinct mixing processes near the mouth of the Bay of Fundy. Finally, all of the along shore flows are influenced by the Jordan Basin (abstract by Pettigrew et al., this volume), which is also a site of comparative studies of particulate flux dynamics between the eastern and western Gulf of Maine (Pilskaln et al., this volume). These areas span the international border and thus there would be great benefit from a coordinated effort. The Bay of Fundy and Penobscot Bay are of broad environmental interest (e.g., recent workshop on Fundy Issues, Wolfville, Nova Scotia., February 1996; Penobscot Bay Workshop, Searsport, ME, March 1996), and the region as a whole supports important commercial fisheries for finfish and invertebrates, aquaculture operations, interest in cod enhancement, populations of seabirds and whales, and many other wildlife and scenic values.

Research Needs

The research needs listed here follow the rationale developed in the previous section. We developed a focus on the northwestern Gulf of Maine as a geographical region which has much to offer a coordinated scientific effort. Many of the topics identified have Gulf-wide application, however, and the focus is not intended to detract from similar studies in other areas. In fact, if one considers the many studies going on around the Gulf of Maine, the focus on the northwestern Gulf can be seen as addressing a relative "low" in the distribution of information and activity. Likewise, the regional framework is established around a few named species, while there are numerous species and processes of potential interest in the region. We did not even enter the trophic levels of fishermen, seals, whales or birds, though we recognize they are interesting and important parts of the system. We leave the elaboration of details and new ideas to the creativity of others whom we hope will write proposals to study here. Finally, we treated modeling as a cross-cutting theme and have not explicitly made recommendations on this topic. With the above caveats, we identified several research needs visàvis life cycles and physical processes.

1. An extension of studies on harmful algal blooms into the eastern Gulf of Maine and, in general, east and west, a continuation of efforts to develop predictive models of bloom development and advection.
2. An extension of oceanographic work focusing on trophodynamics, behavior, vertical mixing, advection and ecology of larval cod from recent large-scale programs (Cod and Climate Change, OPEN and GLOBEC) to the coastal zone. How transferable is our knowledge? What is unique about the coastal zone for this species? What are the dynamics of water mass exchange between coastal (inshore) waters and offshore (Coastal Current and Gulf of Maine) waters? This requires an interdisciplinary effort including physical oceanography, meteorology, plankton ecology and modeling, all at several distinct but interconnected scales. Some of these questions may be explored in a generic way in coastal waters around the Gulf, but the bearing of many disciplines upon the problem necessarily requires a focus for thorough study. For reasons elaborated elsewhere, we recommend that Penobscot Bay be considered for this problem.

3. What conditions (biotic and physical, pelagic, and benthic) make a good inshore spawning ground? This question arises from the recent survey of historical spawning grounds and the interest in reestablishing a coastal fishery. Where do we start? Is enhancement feasible? What is required? What are the coupled habitat requirements and trophic interactions at all stages of life history for a coastal population of cod and other important species of fish or invertebrate, of which there are several in the area?
4. What interactions and exchanges are there between coastal inshore populations or life stages (e.g., in large coastal bays such as Penobscot Bay, Bay of Fundy and the adjacent nearshore regions); those in the major along-shore flows: Eastern Maine Coastal Current (EMCC) and Scotian Shelf inflow; and the "offshore" waters of Jordan Basin? What is unique about each region and water body, including the biological-physical interactions that determine production characteristics, and what is significant about the interactions between the various regions?
5. What physical and biological processes contribute to patterns of distribution and usage of the environment by upper trophic levels such as humans, seals, whales, and birds.

References

Churchill, J. H. 1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. *Continental Shelf Research*, 9:841-864.

Glenn, S. M., and W. D. Grant. 1987. A suspended sediment stratification correction for combined wave and current flows. *Journal of Geophysical Research*, 92:8244-8264.

Sullivan, B. K., P. H. Doering, C. A. Oviatt, A. A. Keller, and J. B. Frithsen. 1991. Interactions with the benthos alter pelagic food web structure in coastal waters. *Can. J. Fish. Aquat. Sci.*, 48(11):2276-2284.

Land/Water Interface: Biogeochemical Cycles, Natural and Perturbed

Donald C. Gordon, Jr.
Bedford Institute of Oceanography

Working Group Members:

Joseph Arbour, Environment Canada
Hanneke Baretta-Bekker, Danish Hydraulics Institute
Claudia Benitez-Nelson, Woods Hole Oceanographic Institution
Heather Benway, University of New Hampshire
Michael Bothner, U. S. Geological Survey
Robert Boudrow, University of New Hampshire
Marilyn Buchholtz ten Brink, U. S. Geological Survey
Matthew Charette, University of Rhode Island
Robert Chen, University of Massachusetts at Boston
Gail Chmura, McGill University
Catherine Coniaris, University of New Hampshire
Catherine Demos, U. S. Army Corps of Engineers
John Farrington, Woods Hole Oceanographic Institution
Donald Gordon, Department of Fisheries and Oceans Canada
Lisa Graziano, Bigelow Laboratory for Ocean Sciences
Barbara Healy, University of Massachusetts at Boston
Ken Jacobs, University of New Hampshire
Norbert Jaworski, U. S. Environmental Protection Agency
Carolyn Jordan, University of New Hampshire
Maureen Keller, Bigelow Laboratory for Ocean Sciences
Theodore Loder, University of New Hampshire
Caroline Martorano, University of New Hampshire
Bradley Moran, University of Rhode Island
Byard Mosher, University of New Hampshire
Steven Pike, University of Rhode Island
Wilfred Pilgrim, New Brunswick Department of Environment
Vicki Pilon, University of New Hampshire
Cynthia Pilskaln, University of Maine
Elva Romanow, University of Massachusetts at Boston
Steven Rudnick, University of Massachusetts at Boston
Marie Studer, Massachusetts Bays Program
Bruce Tripp, Woods Hole Oceanographic Institution
Penny Vlahos, University of Massachusetts at Boston
Gordon Wallace, University of Massachusetts at Boston
Phil Yeats, Department of Fisheries and Oceans Canada
Vlado Zitko, Department of Fisheries and Oceans Canada

Summary

There is need to continue expanding our knowledge of the many sources of major elements and contaminants to the Gulf of Maine. The best known of these are atmospheric and river inputs. More attention must be given to understanding the transformation processes that take place within the Gulf of Maine watershed and how they are influenced by the changes in land use that are taking place. We also must investigate the potential importance of ground water as an important source along the coastline. Other source terms that have not received adequate attention are the sediments of the Gulf of Maine and water exchange at the seaward boundary. In general, our knowledge of contaminant sources and distribution is better for the inshore region of the Gulf of Maine than it is for the offshore. Future studies must address the episodic nature of many of the inputs.

Fundamental to understanding the cycling of major elements and contaminants in the Gulf of Maine is developing a much better understanding of primary production and material transfer processes within the entire ecosystem. In particular, we need to develop a much better understanding of sedimentation processes as well as those processes that affect flocculation and the exchange of materials between water and sediment (both suspended and deposited). We also need to give increasing attention to understanding the role that benthic communities, including microbes, have on the cycling of major elements and contaminants. Again, future studies must take into account the episodic and patchy nature of many of these processes.

There continues to be a very strong need to continue the development of long-term data sets through various monitoring programs. These should be well-designed to address specific hypotheses and coordinated on a Gulf of Maine-wide basis. They should include the broad range of habitats that are present, both inshore and offshore, and take advantage of new advances in measurement technology, including both moorings and remote sensing.

Easy access to data and information is critical to improving our understanding of the Gulf of Maine system. Much valuable data lies buried in the grey literature, filing cabinets and computer files. Existing data (both published and unpublished) should be entered into easily accessible data bases with the necessary quality assurance/ quality control precautions. This should include data on sources, concentrations in different environmental compartments and major transfer processes. Such a Gulf of Maine-wide data base system should also capture new data as they are collected.

There is need to develop a broad suite of interactive biogeochemical models that can build upon the excellent advances that have been made in modeling the circulation in the Gulf of Maine. These should include relatively specific process models as well as more general system models. System models should be developed for different spatial and temporal scales depending upon the different questions being asked. The development of system models should include both mass balance budgets of major elements, contaminants and sediment as well as ecosystem models which simulate the cycling of carbon, nitrogen, phosphorus and silicate. Both types of system models should incorporate all major source and sink terms and also consider the importance of episodic events and patchiness. Such models will help to elucidate the important linkages between the inshore and offshore regions of the Gulf of Maine for both major elements and contaminants.

Full use must be taken of the new technologies that are becoming available for collecting field data at increased spatial and temporal resolution, in both research and monitoring programs. These include *in situ* sensors on moorings and remote sensing.

Finally, it is very important to break down the barriers that often exist between scientists and managers. The key to this is improved two-way communication regarding research questions, priorities, project design and information products.

Introduction

This working group was attended by approximately forty people. In a brief opening plenary session, it was decided to break into three subgroups, one dealing with major elements (e.g., carbon, nitrogen, phosphorus, etc.) and two with contaminants (both organic and inorganic). Each subgroup was assigned a chairperson (Ted Loder, Phil Yeats, Bruce Tripp) and rapporteur (Norbert Jaworski, Heather Benway and Marilyn Buchholtz ten Brink).

All participants were supplied with a list of general questions prepared before the workshop to help structure the discussion if necessary but the subgroups were free to go in any direction they wished. However, they were asked to structure their reports around two general questions: a). What have we learned during the past five years about the biogeochemistry of the Gulf of Maine and b). What are the research priorities for the next five years?

At the end of the day, the chairpersons and rapporteurs of each subgroup prepared a written summary of the deliberations. These subgroup reports were integrated that evening by the working group chair (Don Gordon) for verbal presentation the next morning and were later used after the workshop as the basis for preparing this written summary. The first draft was reviewed by the subgroup chairpersons and rapporteurs while the second draft was sent to all participants for comment. All comments received were considered in preparing the final draft of this report. An effort was made to ensure that this report reflects the subgroups' discussions and is not influenced unduly by afterthought.

It should be emphasized that the output of this working group is very much influenced by time constraints (only four to five hours were available) as well as the particular interests of those scientists participating. It would probably have been much different if there had been more time to reflect on the subject and if other people had participated. One area of contention, that was never resolved, was the relative importance of nearshore processes (including watershed delivery) compared to offshore processes in understanding the biogeochemistry of the Gulf of Maine as a whole. Clearly, this report does not necessarily reflect the consensus view of the entire Gulf of Maine research community. In some cases there is overlap with other working groups and there are undoubtedly important biogeochemical topics that were not addressed. Nevertheless, this report should serve as a useful document for helping to set priorities for biogeochemical research in the Gulf of Maine for the next few years.

Status of Our Current Understanding

On a world-wide basis, the Gulf of Maine is a data rich area. It is surrounded by many scientific institutions with world class expertise and a long history of scientific research. A considerable amount of new research has been conducted since the 1991 Woods Hole workshop under various programs including, but not limited to, the Regional Marine Research Program, U. S. GLOBEC Georges Bank Program, ongoing federal, state and provincial programs in both the United States and Canada, and the Council on the Marine Environment. Some examples of recent scientific accomplishments include:

Major Elements (Carbon, Nitrogen, Phosphorous)

There is now a much better understanding of the general circulation of the Gulf of Maine which in turn has improved our understanding of biogeochemical cycles. It has been demonstrated that fluvial and atmospheric inputs into the Gulf of Maine are episodically driven. We now have better data on the inputs of inorganic nutrients to the Gulf of Maine as well as their concentrations in offshore regions, in particular nitrogen. For example, the most important source of macronutrients to the Gulf of Maine system is the inward advection of offshore water. It has been demonstrated that nutrients are enhanced to some degree in a limited number of coastal embayments due to human activities.

In addition, work currently in progress will provide in the near future new information on:

- The Gulf of Maine coastal current and how it affects the biogeochemistry of coastal waters, including the dynamics of toxic phytoplankton.
- The seasonal variability and magnitude of aeolian and fluvial inputs as well as the source of these inputs.
- The role of current structure in the nutrient dynamics of Massachusetts Bay.
- The coupling of deep current structure with nutrient concentrations in order to get estimates of mass transport.
- The role of internal waves in nutrient transport.
- Primary production estimates and phytoplankton distributions in the Wilkinson and Jordan Basins during the spring bloom.
- Gulf of Maine-wide organic and inorganic calcium carbonate ($CaCO_3$) estimates of primary production and optical backscattering due to $CaCO_3$.
- Estimates of ^{234}Th-derived particulate export (particulate organic carbon [POC], particulate organic nitrogen [PON]) in Wilkinson and Jordan Basins.
- Sediment trap estimates of particulate export (POC, particulate inorganic carbon [PIC], PON)

Contaminants

There is improved knowledge on the concentration and distribution of contaminants in estuarine and nearshore regions of the Gulf of Maine. For example, there have been significant advances in the identification of contaminant sources and assessment of their magnitude (e.g., Boston Harbor, atmospheric mercury). Furthermore, point source inventories and initial non-point source models are now available for anthropogenic contaminants in the Gulf of Maine.

There is improved understanding of the sediment-water interface exchanges of contaminants, including rates and speciation (both metals and organics), and the mechanisms of small-scale cycling of contaminants between sediment and porewater and between sediment and the overlying water column. There is also improved understanding of suspended particle-water exchanges, including new information on vertical fluxes obtained by sediment traps.

There is improved understanding of the significance of physical/chemical phases and speciation of contaminants in relation to biological availability and enhancement of our knowledge of the linkages between biological activity/organic matter and contaminants (e.g., the coastal current study and red tides). Development of new *in situ* continuous sensors and samplers for ocean chemistry has progressed, these will be important for future contaminant assessment and monitoring programs.

The development of physical/biogeochemical process models on different temporal and spatial scales has enhanced our understanding of the distribution and transport of contaminants in the sediment and water column. Inherent in this development are significant advances in the measurement of rate constants and partition coefficients.

Recent advances in physical oceanographic modeling of the Gulf of Maine are very important to biogeochemical cycling. We can now begin to apply these to contaminant transport and incorporate chemistry into models. For example, it has been demonstrated that tracers such as Rhodamine dye can be used to follow the movement of contaminants through the marine environment. The use of models and tracers such as these provides the opportunity for developing contaminant transport models with large spatial and temporal scales.

Science has been integrated into the management of Boston Harbor which is one of the most significant point sources of contaminants to the Gulf of Maine. Contaminant distributions in sediments have been mapped and decreases in the metal concentrations of surface sediments in response to source reduction have been demonstrated. The need for public education on contaminant distribution has been recognized and initial steps taken to make this information available through websites, brochures, etc.

Research Needed

Despite the extensive environmental data base that is available for the Gulf of Maine region, there remain large gaps in the information needed to understand how the natural system functions and the effects of human influence. This information must be in hand if we are to answer adequately the important questions being raised by environmental managers. The working group identified the following requirements for future research. These are presented according to general headings. There was not sufficient time to discuss and agree upon priorities. It is recognized that the separation of discussion into the two major themes of natural elements and contaminants is somewhat arbitrary and resulted in considerable overlap. Integration of research needs and priorities would have been desirable if time had allowed.

Major Elements (Carbon, Nitrogen, Phosphorus)

Sources

While the magnitude of various fluxes of nutrients into the Gulf of Maine as a whole are better understood, we need additional information on source/receptor relationships. Atmospheric deposition, land use changes and the cycling of major elements within the Gulf of Maine watershed are key processes which can have an important impact on the coastal ecosystem. Understanding these relationships is critical to the effective control and management of non-point sources. We need to define the "airshed" of the Gulf of Maine ecosystem for major elements (e.g., nitrogen) and important contaminants (e.g., mercury). This involves identifying source locations, magnitude of emissions, meteorological transport pathways, removal and transformation processes during transport, depositional processes, and transport and storage processes in terrestrial ecosystems. For example, a source/receptor model was recently constructed for the Chesapeake Bay in order to evaluate the effects on water quality which would result from changes in emissions mandated by the Clean Air Act. We must develop a predictive capability to understand the effects that changes in emissions and land use practices will have on the Gulf of Maine ecosystem.

While there was considerable debate over the relative importance of nearshore processes to the Gulf of Maine system as a whole, some working group members felt there is need to develop a better understanding of the influence of land use and land cover on the delivery of carbon, phosphorus and nitrogen by freshwater to the Gulf of Maine. This research should include:

- Examining the relationships between various categories of land use and land cover (e.g., industrial, urban, agricultural, wilderness, etc.) and nutrients contained in the runoff,
- Assessing how changes in natural hydraulics over the last 300 years due to engineering structures such as dams, dikes and causeways, as well as infilling, have influenced the discharge of major elements, sedimentation and other key physical/chemical processes in the coastal zone,
- Expanding and improving terrestrial modeling,
- Coupling terrestrial models with environmental models of nearshore areas,
- Examining the transport and cycling of nutrients within river systems in order to assess the fate of these nutrients and the extent to which they will be transported to nearshore waters,
- Assessing various techniques to control/reduce discharges of nutrients and contaminants to nearshore waters, and
- Examining the significance of atmospheric deposition of nutrients and contaminants to the Gulf of Maine, both in regard to quantity and impact on biogeochemical processes.

It has been suggested that the ratios of nutrients in rivers entering the Gulf of Maine have changed in recent years due to human activities. If so, we need to understand more about the effects of these potential changes on phytoplankton communities and overall trophic structure. For example, it has been hypothesized that changes in nutrient ratios may produce more favorable conditions for noxious or toxic algal blooms. These hypotheses should be tested.

The majority of fresh water input to the coastal Gulf of Maine occurs during the spring (March to June). This freshwater influx contributes to water column stability and the setting up and maintenance of the western Gulf coastal current. It also provides a nutrient impulse. For example, in the Kennebec River over 50% of the annual dissolved inorganic nitrogen (DIN) input to the coastal zone occurs between mid-March and mid-April during the spring bloom period.

The overall importance of this DIN pulse (as well as similar pulses of phosphorus and silicate) is unknown. This raises the following questions that need to be addressed before the significance of these pulses on biogeochemical mass balances and biological communities can be assessed:

- Does the amount of the nitrogen (N), phosphorous (P) and silicon (Si) in rivers add significantly to the overall coastal nutrient budget?
- What is the significance of N, P and Si pulses to spring bloom dynamics in coastal waters? Do they enhance and/or extend the bloom and do they control species type?
- What are the critical/non-critical times of the year for the input of riverine nutrients to the coastal zone? It is expected that a large input of nutrients during the winter may have no significant biological effect while it could have a large effect during the spring, summer and early fall periods.
- What processes control the concentrations of nutrients in the rivers? This involves a better understanding of the effects of land use, the magnitude of municipal and atmospheric inputs and, most importantly, nutrient transformation processes in the rivers themselves.
- And finally, what is the interannual variability of riverine delivery and what long-term changes in fluxes may be taking place and how might they be affecting both biogeochemical cycling and biological communities in the coastal zone?

Little attention has been given in the past to studies of groundwater yet recent studies suggest that groundwater may be very important in the transport of nutrients and contaminants to the coastal zone. It is possible that delivery of nutrients and contaminants to the Gulf of Maine by groundwater seepage could be equal to that of rivers. A spatial study of nutrients and contaminants in rivers and groundwater along the coast, coupled with naturally occurring radio tracers, would provide valuable information on input rates and the relative importance of these two sources to the coastal zone. Groundwater input must be considered in the development of mass balance budgets.

Cycling of Major Elements and Process Studies

Despite the extensive research that has been done in the Gulf of Maine, we are still unable to construct complete budgets of carbon, nitrogen and other major elements because of missing information. Primary production, which is controlled by light and nutrients, drives the Gulf of Maine ecosystem yet data on primary production in the Gulf of Maine are limited. We need to develop a more much complete understanding of primary production throughout the entire Gulf of Maine. For most of the Gulf of Maine, primary production is dominated by phytoplankton but the important contributions of seaweeds, sediment microflora and saltmarshes along the coastline must not be overlooked. We also need to improve our understanding of how carbon and the major nutrients cycle through the food web in both inshore and offshore areas of the Gulf of Maine. This should include collecting data of various export terms.

It is known from the literature that there are different pathways for phytoplankton primary production depending upon environmental conditions. Under some conditions, carbon is transferred directly up the classical food web to higher trophic levels. Under other conditions, it can enter the microbial food web via bacteria and either be transferred to higher trophic levels or remineralized. It is also possible that during the spring bloom a large portion of the primary production can sediment out of water column and provide an important input of carbon to benthic communities. More research should be done on the relative importance of these different pathways in the Gulf of Maine ecosystem and the environmental factors controlling them. It is important that this research be carried out on different spatial and temporal scales. Appropriate temporal scales range from short-lived episodic events affecting nutrient availability to interannual variability. New data on element cycling will contribute to the development of ecosystem models.

Many contaminants are associated with large, rapidly settling particles. These include both particle reactive contaminants (e.g., lead, mercury, polychlorinated bi-phenyls [PCBs], poly-aromatic hydrocarbons [PAHs]) and bioaccumulated contaminants. Sedimentation processes are a key pathway for the removal of contaminants from the water column. Limited data from the central basins in the Gulf of Maine suggest that perhaps as much as 50% of the gross primary production at specific times of the year could exit the euphotic zone in large particles which might also remove large concentrations of contaminants as well. Therefore, it is important that we improve our understanding of contaminant/particle interactions and sedimentation processes throughout the Gulf of Maine. ^{234}Th disequilibria with its parent nuclide ^{238}U can be coupled with contaminant/^{234}Th ratios to estimate their flux rates from the euphotic zone anywhere in the Gulf of Maine with relative ease.

In future research, the scientific community must consider the importance of episodic events (a short duration temporal phenomenon) and localized patches (a spatial phenomenon). This requires a true paradigm shift because we tend to underestimate the importance of short temporal and spatial scales and give more weight to the larger scales. If a pulse of inorganic nitrogen is detected and is several orders of magnitude above normal levels, it can influence an annual mean considerably.

We know that river discharges are episodic and that about 90% of fluvial transport into the Gulf of Maine occurs less than 25% of the time (e.g., three months). A buoyant river plume entering the nearshore zone of the Gulf of Maine may represent a small volume of water relative to the entire water column but it is a much larger fraction of the euphotic zone. Thus, its impact on the productivity in the nearshore zone may be much greater than its relatively small volume might suggest. Furthermore, the timing of the maximum river discharge usually coincides with the period of maximum primary productivity (i.e. spring bloom) so again the impact of the episodic and spatially-restricted spring plume in the nearshore zone may be underestimated if it is based on 'mean' conditions.

In offshore regions, there appears to be a rather close coupling between primary production and secondary consumption for most of the time with the result that a limited amount is exported to deeper water under average conditions. However, there can be conditions, such as the annual spring bloom, when zooplankton populations can not grow fast enough to graze down the phytoplankton and, as a result, a large fraction of the bloom sinks out of the euphotic zone. Episodic events such as this may provide a large amount of the production needed to support the benthic community for the entire year. This is an example of how an episodic event may drive almost 100% of an important exchange process.

Our models and monitoring systems must have the temporal and spatial scales needed to capture and resolve these important episodic and patchy events.

Monitoring

There is a clear need for the development of long-term data sets which document spatial and temporal changes in key variables, including episodic events. While some data bases are currently being collected, this effort should be expanded. Ideally, we need a well-coordinated Gulf of Maine-wide monitoring program based on a series of onshore-offshore transects that are sampled at least once a month. Variables measured should include temperature, salinity, current speed and direction, sediment, natural and anthropogenic radiochemical tracers, organic and inorganic contaminants, nutrients, primary production, POC, PON, particulate organic phosphorous (POP), standing stocks of important biological communities, etc. At certain times of the year, more frequent data collection would be necessary to capture episodic events. The spatial scale of sampling should be such that we can resolve general patterns in the distribution of primary production and other fundamental processes. These data sets will be needed to help build realistic models of both important processes and the overall Gulf of Maine ecosystem.

The task of collecting long-term data sets is not as daunting as it used to be because of the development of new technology which continues to mature at a rapid rate. We are no longer completely dependent upon ships but increasingly can make use of different types of moorings and remote sensing tools that can provide high quality data at small temporal and spatial scales.

It is also recommended that attention be given to the analysis of key chemical variables in sediment cores from around the Gulf of Maine which can be dated with precision. Such an analysis would provide a historical picture of how biogeochemical conditions have changed over the past several hundred years due to human activities.

Data Management

It is important that all existing data sets for carbon, nitrogen and phosphorus for the Gulf of Maine be compiled and archived. This should include both important standing stocks and transfer rates. Once compiled, these data sets should be made freely available to the scientific community through electronic media such as EDIMS. These data sets will have many applications including model development and providing insight into spatial and temporal changes in element concentrations and their ratios.

Modeling

Existing budgets of carbon and nutrients for the Gulf of Maine are incomplete. We need to develop the next generation of mass balance budgets using the data that have been gathered in recent years. We should refine the existing first order budgets of carbon, nitrogen and phosphorus where they exist and also develop new ones over different spatial scales including the northwest Atlantic, the entire Gulf of Maine system, and selected areas of the Gulf of Maine, especially in the coastal zone.

In addition to quantifying major input and export processes, these budgets can be used to test different hypotheses about changes in the Gulf of Maine system, for example that nutrient enrichment has not affected nearshore fisheries. It would be valuable to compare budgets of present day conditions to those fifty to one hundred years ago to see if there are changes in fluxes and nutrient ratios due to human activities (e.g., land use, emissions, engineering works, etc.) that may have impacted coastal habitats.

The development of large scale ecosystem models should be pursued to help improve our understanding of biogeochemical processes in the Gulf of Maine. The development of such models should be based upon our current understanding of carbon, nitrogen and phosphorus cycles in the Gulf of Maine supplemented where necessary with data from similar natural systems in the world such as the North Sea. These models should incorporate all geographic regions of the Gulf of Maine and should include estuarine and watershed processes. They should also include food web dynamics. Mixing processes between spatial compartments should be driven by the excellent circulation models that are now available for the Gulf of Maine. Model building will require the processing and archiving of existing data, such as climatological nutrient distributions.

New Methodology

We are about to enter a new era in remote sensing with the recent launch of the Ocean Color and Temperature Sensor (OCTS) in August 1996 and expected launch of SEAWIFS in May 1997. For the first time ever, we will have the ability to obtain Gulf of Maine-wide synoptic maps of phytoplankton pigments for every clear day. This temporal coverage is similar to sea surface temperature (AVHRR) satellite data but vastly superior to the Coastal Zone Color Scanner (CZCS) which ceased operating

ten years ago. The new class of ocean color sensors will allow us to view turbid river discharge plumes and to assess sediment concentrations. Their spatial resolution will be about 750 m for OCTS and about 1100 m for SEAWIFS. We will also be able to assess the role of episodic events such as storms on the transport of materials into the Gulf of Maine via rivers, and phytoplankton blooms resulting from destratification in deep basins.

To lay the scientific basis for interpreting satellite ocean color data, we need to improve our optical models. Specifically we need to parameterize radiance models for local/regional particle types. Different rivers have their own spectral signatures which results from a characteristic mix of organic and inorganic particles.

We should also make full use of long-term optical moorings for monitoring water quality in nearshore embayments, estuaries and harbors. This technology is only just maturing and it will soon be both practical and feasible.

Contaminants

Sources and Distribution

In general, we have better knowledge of contaminant distributions in the nearshore region for the Gulf of Maine than we have for the offshore. Coastal hot spots have been identified. However, we need additional information on the sources of key contaminants to the Gulf of Maine, in particular the atmosphere, rivers and groundwater.

Despite recent advances in knowledge, many point sources of contaminants around the Gulf of Maine are still not well characterized, including the variability in loadings with time. Generally speaking, we should expect reductions in point source as controls are tightened but they may still be the dominant loading. It is important to understand the relative magnitude of point and non-point sources. Non-point sources are much more poorly characterized and vary greatly with land use. They may perhaps have different forms of chemical speciation. Riverine loadings are fairly well known and can represent a net watershed signal. Atmospheric loadings of contaminants in the Gulf of Maine are poorly known, as is the input from oceanic waters outside the region.

While there is still need to collect more information on the sources and distribution of contaminants in the nearshore region, we have an even greater need for contaminant data in the central Gulf of Maine where the database is more limited. This information is important for identifying and quantifying potential offshore sources of contaminants and understanding possible exchanges with the nearshore zone.

We need to develop more and better site-specific inventories and mass balances of key contaminants (e.g., herbicide use in a given watershed). More accurate inventories of known sources and knowledge of contaminant distribution will help identify significant sources and pools of contaminants, provide insight into patterns of distribution and identify data gaps. These inventories and mass balances should be done on appropriate scales ranging from a watershed or an estuary to the entire Gulf of Maine.

It is suggested that the priority of studies should be influenced by the potential of a particular contaminant to accumulate and attain levels that are dangerous to biological communities. For example, short-lived contaminants should probably be given low priority.

Fluxes and Process Studies

There is a general need to expand our knowledge of the numerous processes which influence the flux of contaminants through the Gulf of Maine system. These include atmospheric and freshwater (both river and groundwater) delivery, partitioning, flocculation, scavenging, advection, sedimentation, resuspension (both natural and human-induced), bioturbation and burial. We also need to increase our understanding of the coupling of nearshore and offshore processes affecting contaminant transport.

We need a much better understanding of contaminant speciation and association with particles which has relevance to understanding factors such as the vertical flux of contaminants in the water column, biological availability and sediment toxicity. We also need to improve our knowledge of the transport and partitioning of particle-bound contaminants during resuspension events (both natural and human-induced) to better resolve temporal and spatial variability in distribution as well as how suspended particle - water exchange processes affect the vertical transport of contaminants.

We need to assess the role of the various forms of organic matter (e.g., POC, DOC, and colloidal organic carbon [COC]) in contaminant transport. The composition of organic matter can vary considerably in different areas of the Gulf of Maine. The production of organic matter is influenced by inorganic nutrients.

Because of the close association of contaminants with particles, we need to develop detailed sediment budgets for different geographic regions of the Gulf of Maine. This requires information on sources, sedimentation rates, transport and rates of accumulation. It is particularly important to identify the major depositional areas in the basins of the open Gulf of Maine. It is equally important to develop a good historical record of contaminant accumulation in carefully sectioned and dated cores. This will provide a retrospective look at trends over recent history.

Monitoring

There is a continuing need to develop long-term data records of key contaminants to document spatial variability and to identify temporal trends. Monitoring programs should be hypothesis driven and include all the variables necessary for modeling contaminant distribution and mobility. They should focus on contaminants of most immediate concern to scientists and managers and be done at process relevant scales. Monitoring needs and strategies should be assessed in light of increased scientific understanding of expected changes, contaminants of concern and expected zones of impact and objectives clearly defined collaboratively by scientists and managers.

Data Management

We need to improve our databases on contaminant sources and distribution in the Gulf of Maine system. These databases must also include information on analytical results and sample availability. In constructing these databases, attention must be given to quality assurance/quality control (QA/QC) of older data. These databases must be easily available so that the information is accessible to all potential users. The need for information sharing can not be over emphasized. In particular, scientists should give increased attention to the information requirements of managers, for example bibliographies, edited data and data interpretation.

Modeling

We need to develop and verify (i.e. field test) geochemical models of sediment-water fluxes and suspended particle-water interactions. These will help to determine the processes (e.g., speciation, buffering, etc.) that control partitioning and provide further information on sensitivity to different variables.

On large scales, we need to integrate contaminant geochemistry process models into physical oceanographic circulation models and models of particle transport (e.g., add partitioning coefficients to physical models). Initially, coarse-scale models (e.g., box models) may be adequate to address geochemical concerns. For more complicated problems requiring a multidisciplinary approach, integration with more complex physical oceanographic models will be required.

New Methodology

We need to develop new methods and instrumentation for measuring contaminant concentrations and processes at much higher temporal and spatial resolution then we have done in the past. At the same time, we need to continue the development and testing of new sensors for detecting contaminants under *in situ* and continuous conditions. Wherever possible, these new methods should strive to be faster, cheaper and more precise. Once the capability of new instruments is verified in the field, we should start to use them in both monitoring and research programs. This instrumentation will allow us to develop a much better understanding of natural variability and how to distinguish it from human-induced changes. There also is a clear need to develop better methods for measuring the potential adverse effects of contaminants, including bioavailability.

Response to Management Needs

The importance of responding to the needs of environmental and fisheries managers was well recognized and generally accepted. However, the point was made that the scientific community needs a clear understanding of how the natural system functions before it can answer management questions with confidence. This includes understanding the variability of natural elements and contaminants and the processes affecting their supply, transformation and sinks. Many system changes initially thought to be due to human influence may in fact be natural in origin.

Questions raised by managers can serve as the basis for designing excellent and intellectually challenging research programs. The needs of managers, as well as feasibility (cost and level of effort) and scientific interest, should be considered in establishing research priorities and allocating funding. Managers should also be involved wherever possible in the design process itself, such as selecting the priority contaminants to be investigated or in establishing new monitoring programs.

As well as addressing the key issues raised by managers, it is also important that scientists deliver the results of the research in usable format. For example, the scientific process usually terminates in the publication of a peer-reviewed paper of interpreted data. Such a product is of limited value to managers who do not have the time to read the scientific literature. They need products of synthesized data such as summaries, guidelines, GIS-linked data bases, user-friendly decision support systems and predictive models, etc. More attention should be given to delivering these products.

A poll of working group members indicated that at least one person is working on thirteen of the sixteen questions posed by managers during the opening panel discussion of this symposium. The four questions which are receiving the most attention by working group members were, in decreasing order of effort: (1) quantitative assessment of cumulative impacts on coastal resources of point and non-point sources on a watershed basis, (2) characterization of the driving forces of change on the Gulf of Maine ecosystem, (3) effects of climate change of the Gulf of Maine ecosystem and (4) habitat changes caused by physical alterations. There is no doubt that much of the biogeochemical research currently being conducted in the Gulf of Maine is highly relevant to the needs of managers which is not surprising considering the targeted nature of present day funding sources.

Human Induced Biological Change

Judith Pederson
Massachusetts Institute of Technology

Working Group Members:

William Ayer, New Brunswick Department of Environment
Seth Barker, Maine Department of Marine Resources
Walter Barnhardt, University of Maine
Margaret Brady, Massachusetts Coastal Zone Management Program
Jean Brochi, U. S. Environmental Protection Agency
Robert Buchsbaum, Massachusetts Audubon Society
Les Burridge, Department of Fisheries and Oceans Canada
Daniel Campbell, U. S. Environmental Protection Agency
Mark Chandler, New England Aquarium
Philip Colarusso, U. S. Environmental Protection Agency
Michael Connor, Massachusetts Water Resources Authority
Chris Cornelisen, Office of Massachusetts Coastal Zone Management
Elizabeth Della Valle, Maine State Planning Office
Stephen Dickson, Maine Geological Survey
Peter Eaton, Environment Canada
Alison Evans, Department of Fisheries and Oceans Canada
Marie Evans, University of New Hampshire
Gordon Fader, Geological Survey of Canada
Tim Ford, Harvard University
Gareth Harding, Department of Fisheries and Oceans Canada
Larry Harris, University of New Hampshire
Kats Haya, Department of Fisheries and Oceans Canada
Mary Hayes, Maine State Planning Office
Peter Hennigar, Environment Canada
Susan Holtz
Nick Houtman, University of Maine
William Hubbard, U. S. Army Corps of Engineers
Irena Kaczmarska-Ehrman, Mount Allison University
David Keeley, Maine State Planning Office
Joseph T. Kelley, Maine Geological Survey
John R. Kelly
Matthew Liebman, U. S. Environmental Protection Agency
Cathy MacKenzie, Washburn & Gillis Associates Ltd.
Michael Moore, Woods Hole Oceanographic Institution
Laura Mucklow, Cantox Inc.
Judith Pederson, Massachusetts Institute of Technology
Bob Rutherford, Department of Fisheries and Oceans Canada
Jack Schwartz, Division of Marine Fisheries
Glyn Sharp, Department of Fisheries and Oceans Canada
James Shine, Harvard University
Darrell Taylor, Nova Scotia Department of the Environment
Gordon Tidmarsh, Texaco Canada Petroleum Inc.
Megan Tyrrell, University of New Hampshire
Page Valentine, U. S. Geological Survey
Peter Wells, Environment Canada
Louise White, Department of Fisheries and Oceans Canada

Introduction

The plenary talks on Human-Induced Biological Change focused on examining effects and identifying current areas of interest for which data and information is being collected. The presentations by plenary speakers, poster and other presenters complement another working group session that examines biogeochemical inputs and land-based pollution sources. The four plenary talks presented as introductory discussions about the topic of human-induced biological change only partially address issues in the context of the entire Gulf of Maine, but each paper highlights specific issues that are of topical interest. Together, the plenary papers focus on near-coastal effects for contaminants and examine habitat and alterations further offshore. Human-induced changes have the greatest impacts closest to shore; J. Kelly discusses effects of near-shore discharges and land-based activities; and J. McDowell reviews contaminant effects on marine organisms and populations; and both R. Steneck and L. Watling identify habitats and alteration of habitats within range of commercial and recreational fishing activities.

Each of the four plenary speakers was asked to respond to the following questions:

Have human activities demonstrably affected biological populations?

Are the problems we are attempting to solve today, the critical ones of tomorrow?

How can we distinguish meaningful problems and concerns from issues that become the cause celebre of the hour, but which detract from addressing and redressing real issues?

Can we determine if the system can rebound from the impacts?

Many of these questions are unanswerable at this time and the plenary papers, together with relevant abstracts provided background on selected issues. Two issues not addressed in the plenary session were (1) the impacts of sewage related discharges that are responsible for water borne diseases and (2) causes (e.g., sewage, animal wastes, and illegal hook-ups) of shellfish bed and swimming beach closures. Similarly, the plenary speakers did not address impacts to wetlands, marshes and subtidal areas that are important coastal habitats.

Poster session abstracts, reported in this volume, that did address these topics were M. Connor et al.'s review of management concerns related to waste water disposal and M. Chandler et al.'s examination of eelgrass bed distribution in an urban harbor.

Other relevant abstracts examined the sensitivity of embayments to sewage inputs, often from non-point sources such as septic systems, agricultural runoff and residential areas. Several of the abstracts indicated the relevance of these issues throughout the Gulf, and there were two others that looked at specific organismic responses to contaminants (M. Moore) and effects of trawling on bottom habitats (P. Valentine).

In this working group session, two general topics were identified for in-depth discussion; 1) Physical Habitat Degradation and Resource Exploitation, and 2) Biological Effects of Contaminant and Nutrient Inputs into the Gulf of Maine. Two working sub-groups were formed to address these aspects of human-induced biological change and habitat alteration and contaminant effects. Both subgroups were given three charges:

1. Develop a set of scientific issues that identify future research priorities.
2. Identify existing ecological models or develop conceptual models that may lead to predicting how communities will respond to specific human activities.
3. Review how the scientific priorities relate to management questions posed by the panelists.

There were approximately twenty participants in each of the two subgroups. Robert Buchsbaum facilitated the session that addressed issues related to physical habitat degradation and resource exploitation, with Jim Shine serving as rapporteur. William Hubbard led the second sub-group that addressed questions related to biological effects of contaminants and nutrients, with Laura Mucklow and Nick Houtman serving as that group's rapporteurs. Both working subgroups developed working statements or conceptual models to guide their discussions, which are presented separately below.

Priority research recommendations from the habitat alteration and resource exploitation working subgroup are:

- Identify and map ecologically sensitive habitats.
- Expand the understanding of critical or essential habitats.
- Establish thresholds for impairment of habitat function.
- Evaluate sediment transport, especially in the Bay of Fundy.

Priority research recommendations from the human-induced contaminants and nutrient impacts working subgroup are:

- Evaluate key environmental issues that result in improved understanding of effects, transport and loading, in that order of importance.
- Focus scientific research on risk/hazard analysis, management (including adopting adaptive management practices), and methods, in that order of importance.
- Identify a series of indicator species.
- Focus attention on specific regions, e.g., Bay of Fundy at a level that improves understanding.

Table 1.
Research Priorities for Habitat Degradation and Resource Exploitation
Specific issues within each category are listed in order of priority within each subset.

Habitat description issues:
- Define, map and identify economically and ecologically important habitats in the Gulf of Maine
- Evaluate the nature of the risks to which these habitats are subjected.
- Determine interactions among and between habitats.
- Prioritize habitats for restoration and determine ways to evaluate success of restoration efforts.

Habitat alteration issues:
- Develop tools to quantify the effects of mobile gear on the quantity and quality of important habitats in the Gulf of Maine.
- Determine thresholds beyond which functioning of habitats are impaired.
- Determine the effect of sediment transport on habitat form and function.
- Determine the effect of sea level rise on habitat quantity and quality.
- Determine the role of exotic/invasive species on habitat form and function.

Science/Policy interface issues:
- Develop a rationale for long-term monitoring of habitat quantity and quality in the Gulf of Maine.
- Insure that the results of scientific research are framed in a form valuable to decision makers.
- Include public education as a tool for improved management of important habitats in the Gulf of Maine.
- Draw on and revisit historical information to aid current habitat protection efforts.

Human Induced Physical Alterations of Habitats and Resource Exploitation

The first working sub-group agreed that habitat research in the Gulf of Maine has the potential to address a large number of the concerns raised by the managers at the beginning of this workshop. The relevance of understanding habitat function is a pressing management concern, combined with the fact that habitats are typically less expensive to study compared to other areas of investigation. Thus habitat alteration is an attractive area in which to do research that provides insights with direct application to management questions. When considering breadth of impacts, habitat alteration issues related to fishing are arguably the major environmental issues facing the Gulf of Maine.

The group identified as a fundamental necessity the value of technical information in the environmental decision making process. In this context, the group struggled with whether this forum was an opportunity for decision makers to tell scientists what their technical information needs are, or whether scientists should lead governmental decision makers by informing them of new issues in habitat research important for management of coastal and marine environments. The decision-making process at the state level is often driven by short-term problems requiring immediate action. Although there was interest in short-term information, the working subgroup discussion was envisioned as an opportunity for decision makers and researchers to discuss opinions, set goals, and determine priorities for long-term understanding and protection of these fragile yet commercially valuable habitats.

A number of people commented that the working group was covering ground that had already been addressed in a number of recent forums, notably two RARGOM workshops about Habitat and Cumulative Impacts and the Bay of Fundy Issues workshop. The session chair said that the goal for the present group was to take the discussion a step further, generating proposals for research from the list of priority issues identified in Table 1.

Identification and Mapping of Economically and Ecologically Important Habitat Areas

Identification and mapping of economically and ecologically important habitat areas were seen as the first priority. It was agreed that complete mapping of the Gulf of Maine was impractical, and that initial efforts should focus on habitat types specific to commercially important species. This initial mapping effort should begin by collecting existing information together in a GIS format. It could start by mapping the geology in and around the following habitat types: major geological features, macroalgae beds, eelgrass beds, salt marshes, and identifying existing and historic fish spawning areas. A next step would be to revisit historic fish-spawning areas to determine if geological changes have occurred due to human-induced impacts such as changes in sediment properties and sedimentation rates. The groups agreed that such a preliminary mapping effort would have Gulf-wide relevance, would be relatively inexpensive and could be completed in a relatively short time. Gradually, additional parts of the geology of the Gulf of Maine could be mapped.

A related priority is a need to expand our knowledge of critical or essential habitats. Two approaches were proposed: a species-based method and a habitat-based method. That is, habitat mapping efforts can be driven by an *a priori* understanding of habitat types important to commercially important species through use of habitat suitability models, or can rely instead on relating presence of species in specific habitats, such as eelgrass beds or cobbles. Both of these efforts require long-term commitments since they require intimate knowledge of specific organisms over all of their life history stages or they require intensive examination of habitats. Current mapping efforts such as those in Passamaquoddy or Casco Bays in which a number of important species of interest have been identified can serve as preliminary information to guide these efforts. One problem to be addressed is that the presence of disturbed habitats makes it difficult to determine if the habitat was a critical habitat in its previous undisturbed state. The data collection effort, although time consuming and expensive, will have a high probability of success and can serve as a valuable tool for management and protection of Gulf of Maine habitats.

Determine the Effects of Mobile Gear on Habitat Form and Function

The second important research priority was to determine the effects of mobile gear on habitat form and function. The ideal research would allow development of a factorial design with some cells being trawled and others serving as control with sufficient replication, to allow meaningful examination of physical condition, invertebrates, and the presence of prey species of relevance to commercially important finfish. A key factor limiting research is the absence of control locations on which to perform controlled drags. It may be scientifically desirable to set aside critical habitat areas for scientific study of restoration of dredged areas after disturbance. However, political concerns make it unlikely that this will happen. Current closures on Georges Bank may offer such opportunities. If these scientific 'refuges' are created, controlled experiments can be funded. It is also important to understand how regions with different geological characteristics respond to the use of mobile gear. Some areas may be more impacted or recover more rapidly than others.

Two important "second level" research areas were described. These were not considered as high a priority in the immediate future as the above issues, but were nonetheless still considered to be of major importance. One was determining the threshold levels beyond which significant alteration of habitat function occurs. Closely related is an evaluation of the size and other landscape characteristics that determine the functioning of a habitat. It was suggested that eelgrass could be used as a model habitat to examine this question. What minimum-size of an eelgrass bed is necessary to enable it to carry out its nursery function and what other landscape characteristics, such as proximity to other eelgrass beds or other types of habitats, affect its functioning. Such an analysis could also be carried out on cobble habitats that are nursery areas for cod or lobsters. This effort is most important to decision makers charged with determining the effect of human activities on the quantity and quality of important habitats.

The second of these important "second tier" issues relates to the transport of sediment within the Bay of Fundy. This was identified as a major issue by the Bay of Fundy Issues Workshop. A number of large changes have occurred in recent years in the distribution of certain birds and marine mammals within the Bay. Such changes could have impacts across the Gulf of Maine. It is believed that these changes are related to alterations of sediment transport resulting from dikes and other human-made structures. To put this in a Gulf of Maine-wide context, the committee suggested funding a study that would examine sediment exchange between the Bay of Fundy and the Gulf of Maine. This would be relatively inexpensive and could be accomplished in a short period of time.

The committee agreed that it is also important to understand linkages between habitats. Does alteration of one habitat affect nearby habitats? Are nearshore habitats linked in any functional way with offshore ones? Since this is a difficult issue around which to design an experiment, the committee suggested that a working group be formed to examine this further. This type of information will help us refine our definition of 'critical' habitats.

Finally, the other issues described above are all worthy of research. The presence of exotic/invasive species may have a significant effect on habitat restoration, and should be investigated to determine if further controls on ballast water handling or aquaculture practices should be implemented. We need also to develop indicators of habitat restoration. Cost effective strategies are required if restoration efforts are to become a standard practice of all projects involving the coastal zone.

The first working sub-group determined that the physical impacts of deposition of clean dredge spoils were localized, hence this issue was not as high a priority as the other previously described.

In summary, two priority areas are (1) identifying and mapping of ecologically sensitive habitat areas and (2) expanding our understanding of "critical" habitats. Additional areas of priority are (1) establishing thresholds for impairment of habitat function and (2) evaluating sediment transport especially in the Bay of Fundy.

Human-Induced Contaminant and Nutrient Impacts

The second working sub-group focused on identifying some examples of critical components of the conceptual sub-model for research priorities related to human-induced contaminant impacts. This group drafted a working statement that guided their subsequent discussion.

We recognize a continuum in the environment of
Loading
Transport
Effects
that precipitates scientific research needs in the areas of
Risk/Hazard Assessment
Management
Research.

The second working subgroup identified many specific issues within each category. However, they recognized that the mega-projects (e.g., drilling on Georges Bank, dredging Boston Harbor) should not be forgotten, and need to move forward, while providing valuable data about real world impacts for evaluation. (It was noted that the following report represents over one hundred man-hours facilitated among a group with cumulatively 360 man years of experience). Issues are listed in descending order of priority and a conceptual budget is provided. The conceptual budget ($50 million) can be used to identify relative importance among the six general categories. Using the working statement to guide discussions, the sub-group first identified priorities in what are termed environmental events under three categories: loading, transport and effects.

Environmental Event

Loading ($2 Million of the $50 Million Conceptual Budget)

Loading from point and non-point sources should be quantified and relative contributions determined as a way of identifying priorities. Compilation of loading inventories can be used to forecast, predict and quantify loading inputs into the Gulf of Maine ecosystem. Once accomplished, the emphasis can shift to understanding the role of non-point source inputs in relation to point and other cumulative stressors. Although often neglected, sediments are a major sink of past and continuing contaminant inputs. As pollution abatement measures remove pollutants, these sediments may become a source, especially during resuspension. Similarly the contribution of atmospheric inputs of contaminants should be quantified and research conducted into the mechanisms of transport and process of uptake.

Long-term planning is needed for addressing regional trends and projected land-use changes as they affect contaminant loadings. Currently, analyses are often limited to single contaminant impacts. However, synergistic effects of chemicals on biological systems, their movement in the environment, and relative risk gain importance and should be a focus of future research. For example, the impacts of noxious algal blooms are documented, but the cause of episodic events is poorly understood.

Transport, Transformation and Fate ($4 Million of the $50 Million Conceptual Budget)

Effects ($16 Million of the $50 Million Conceptual Budget)

Risk/Hazard Assessment ($12 Million of the $50 Million Conceptual Budget)

The endpoint goals and criteria for ecological restoration need to be established for the various degraded habitats in the Gulf of Maine and should be defined by both managers and scientists. The existence and persistence of toxins in our environment need to be considered in the context of goals for reduction, acceptable levels and/or endpoints. A high priority is to understand the effects of contaminants on human health and to select from the global collection of contaminants and focus on those that pose the greatest threat to humans and the ecosystem.

There were several examples discussed and these are used to highlight areas of research.

The biological significance of hydrocarbons as a toxic chemical from runoff, oil extraction and accidental spills should be examined more thoroughly. The behavior of contaminants as conservative or non-conservative entities should be considered in all aspects of toxicity analysis. For example, the bioaccumulation of contaminants from sediments into the benthos and higher trophic levels should be studied in the context of effects to the organisms and populations. The implications of endocrine disruption needs to be evaluated to understand ecological and human health risks. A methodology should be developed and used that is risk based to assess the relative impacts of resource use conflicts such as hydrocarbon extraction.

For example, the Gulf of Maine community should identify the next 3 to 4 years of research that could be useful of conducting ecological evaluations of Georges Bank drilling activities. The final interactions of the Gulf of Maine sub-models should be geared toward defining the long-term resiliency of the entire system.

The survival of human pathogens in marine systems needs better investigation. As the persistence of human pathogens is examined, the increasing virulence and antibiotic resistance of these pathogens must be evaluated. The causes of harmful algal blooms require additional research. The linkage between toxic chemical and biotoxins is likely to gain greater importance with increasing populations. One emerging area of concern is the assurance that aquaculture yield maintains integrity through constant monitoring for toxins and biotoxins.

The transport, transformation, fate, and effect of contaminants are broad in scope with implications for nearly all uses of the ocean environment. The risks and impact assessment of the Gulf of Maine system must be evaluated under the existing conditions of a disturbed system. The importance of taking an ecosystem approach to identification and management of contaminants can not be overemphasized.

Management ($10 Million of the $50 Million Conceptual Budget)

In recognition that the most important action is source reduction, the following question was posed: What are the research needs for optimizing management strategies in the Gulf of Maine?

Long-term research and monitoring needs a management direction in the following areas:

All important human and ecological toxins require scientifically derived ranges for acceptable levels of impact. Case studies need to be developed for regionally significant habitats that allow managers to make decisions in similar habitats based on the scientific knowledge gained from case studies. Sediment quality criteria should be scientifically derived.

Regionally comparable land use and zoning management tools need to be developed. A repository needs to be developed for archiving samples obtained now for future analyses.

Impact assessment processes should be simplified. The techniques and priorities for contaminated sediment remediation also need development. Resource use conflicts for dredging, aquaculture, petrochemical and mineral extraction, fishing and recreation need to be analyzed to develop a management framework (e.g., Canadian Marine Environmental Quality Framework). The usefulness of a comprehensive watershed approach needs to be evaluated in the Gulf of Maine

Managers and the public must be educated in the value of fundamental research. The significant information gaps on George's Bank must be identified and priorities set based on scientific priorities and the public perception of ecological priorities. A forward vision of the possible "unknown" unknowns or discontinuities in ecological processes should be developed for the next generation - 25 to 30 years out. Managers should review priorities for time frames and funding cycles for active research goals proposed by organizations such as RARGOM. Scientific research priorities of managers and scientists must be developed in line with the socio-economic forces.

Methods ($6 Million of the $50 Million Conceptual Budget)

There is a need to improve toxicity testing as tools/indicators to make them more relevant for assessment of risk to biota, ecosystems and human health. Technology must be improved to produce cheap, instant chemical and biological technology ("litmus paper"-type tests) for *in situ* measurements. System wide databases need to be developed to support improvements in interpreting regional data and while maintaining future data warehouses.

There needs to be a better development of analytical tools for complex chemical mixtures. The Gulf of Maine scientific community should conduct interlaboratory comparisons and data validation for all research institutions. Technological improvements need to be made in the area of contaminated sediment remediation. Research is needed in the assessment of remote sensing tools for chlorophyll and other biological monitoring. Finally, all monitoring efforts need a better archive and retrieval system for the duration of monitoring programs and for long-term trend analyses.

The working sub-group noted that given the diverse needs of different areas within the Gulf of Maine, recommendations should be made for ways to narrow down lists and develop conceptual models.
It was noted that efforts were made in developing this conceptual model by dividing it into environment events vs. action:

– environment: loading, transport, effects

– action: management, risk/hazard assessment, research.

Each area, group or entity should keep this conceptual model in mind as specific priorities are addressed. Two general recommendations were offered (1) development of a series of indicator species or surrogates for assessment of long-term trends and public education, and (2) acquisition of more scientific knowledge about the Bay of Fundy, at a level comparable to the current state of knowledge for Massachusetts Bay.

In her plenary talk, Eileen Hofmann challenged conference attendees to develop and articulate a conceptual model for the Gulf of Maine. With a comprehensive, integrated model, the studies and focus of future research activities will be better understood and receive attention from managers, funding agencies and the research community. The Human-Induced Biological Changes working subgroups identified problems and research needs that move in the direction of identifying an understanding of the Gulf ecosystem functions.

Throughout the discussions of both groups, it became clear that "endpoints" or valued components of the ecosystem are not well-defined. From the plenary talks and abstracts, it is clear that fisheries are a major concern, but few integrated Gulf-wide models exist that can be used to focus research priorities. Similarly, sensitive species, critical habitats, ecosystem health and role of restoration are not defined in terms that allow one to set forth clear unambiguous research priorities.

Fishery and Aquaculture Issues

David Stevenson
Maine Department of Marine Resources

Working Group Members:

Robin Alden, Maine Department of Marine Resources
John H. Allen, Huntsman Marine Science Centre
Ted Ames
John Anderson, Atlantic Salmon Federation
Joseph Brown, Memorial University of Newfoundland
Michael Burt, Huntsman Marine Science Centre
Maria-Ines Buzeta, Department of Fisheries and Oceans Canada
Blythe Chang, Department of Fisheries and Oceans Canada
David Coon, Conservation Council of New Brunswick
Robert Crawford, Nova Scotia Department of Fisheries
Brian Doyle, University of New Hampshire
David A. Greenberg, Department of Fisheries and Oceans Canada
Mark Lazzari, Maine Department of Marine Resources
David Libby, Maine Department of Marine Resources
Linda Mercer, Maine Department of Marine Resources
Gilles Olivier, Department of Fisheries and Oceans Canada
John Pearce, National Marine Fisheries Service
Gerhard Pohle, Huntsman Marine Science Centre
Jon Rittgers, National Marine Fisheries Service
Shawn Robinson, Department of Fisheries and Oceans Canada
Rodney Rountree, National Marine Fisheries Service
Daniel Schick, Maine Department of Marine Resources
Susan Snow-Cotter, Office of Massachusetts Coastal Zone Management
David Stevenson, Maine Department of Marine Resources
Laura Taylor, Maine State Planning Office
Richard Taylor, Gloucester Aquaculture Project
Deborah Trefts, Yale University/Dalhousie University
Lou Van Eeckhaute, Department of Fisheries and Oceans Canada
Susan Waddy, Department of Fisheries and Oceans Canada
Brenda Waiwood, Department of Fisheries and Oceans Canada
Ken Waiwood, Department of Fisheries and Oceans Canada
Fred Whoriskey, Atlantic Salmon Federation

Introduction

The Fisheries Working Group divided into two discussion sessions. David Stevenson led the fisheries session, with Dan Schick serving as rapporteur; Ken Waiwood was the discussion leader for the aquaculture session, with Blythe Chang serving as rapporteur. The reports from each subgroup session follow.

Fisheries

David Stevenson

The Fisheries Working Group focused its discussion primarily on the question of how to improve the quality of the scientific advice that is provided to managers. We considered whether an ecosystem-based science and management approach is required and, if so, what it might look like. In particular, we examined the status quo single species approach used to optimize yields from exploited marine fish populations and asked whether it was the right tool for the job. We concluded that Mike Sinclair and other fisheries biologists and marine ecologists who have recently considered these same questions are right: the single species approach is adequate for the job, but needs to be improved so that ecosystem dynamics considerations are incorporated more explicitly into the scientific and research process that produces management advice.

Ecosystem management, as currently applied to some terrestrial and fresh-water ecosystems, has different objectives than does the single species population dynamics assessment and management approach that is applied to most exploited marine fish populations. Although it means different things to different people, the primary objectives of ecosystem management are to preserve biodiversity and maintain the ecological integrity of the ecosystem, not to achieve maximum or even sustainable yields from individual resources that compose the ecosystem.

For a variety of reasons, marine fisheries resources are managed on a single species basis. Some attempts have been made during the past twenty years or so to group species together on the basis of common biological and ecological attributes and to quantify interactions between species (e.g., predator/prey interactions) and between individual species and their physical environment. These early multi-species assessment models were not implemented because they required so much data, most of which was not available. However, the multi-species approach has not been abandoned and the prospects of having some functioning multi-species models in place for the Gulf of Maine in the near future are good. The alternative approach, defining and modeling a simpler "system" that puts ecosystem components and processes into fewer "boxes," has received some attention during the last few years from some ecologists, but was not considered at this Symposium. This approach merits further attention, but we are nowhere near a situation in which a systems model of the Gulf of Maine is going to replace the current single species approach for providing scientific advice to fisheries managers.

The Fisheries Working Group identified a number of deficiencies with the current single species assessment approach that limit its usefulness in accounting for species interactions and environmental variability. If these deficiencies were corrected, single species assessment models would become more multi-species in nature and would at least have an ecosystem context that would allow for more reliable estimates of population sizes and yields under varying or changing environmental conditions or shifts in species composition. Some of these deficiencies are:

- Failure to sufficiently account for the actual distribution patterns and behavior of fish populations when defining unit stocks for management purposes;
- Unreliable or non-existent estimates of recruitment, and a poor understanding of factors affecting recruitment;
- Failure to adequately account for species interactions (e.g., predation, competition) and environmental variables that affect natural mortality rates of target species; and
- Poor understanding of how environmental factors, and trends in those factors, affect the distribution of target species and other species with which they interact, and their vulnerability to fishing effort.

It was noted that species interaction information should focus on the most important relationships since there is an almost endless array of biotic and physical interactions that could be factored into assessment models, but probably don't need to be. To assist in this process, the use of sensitivity analyses that test the response of model results to variations and trends in input parameters is encouraged.

The Fisheries Working Group noted that critical biological and ecological information is often not factored into assessments and recommended that a greater effort be made to include scientists from other disciplines in the assessment process. The Working Group also recommended that assessment reports and biological advice made available to managers include summaries of relevant ecosystem information (e.g., descriptions of key environmental conditions and trends and their effects, habitat utilization, known or suspected interactions with other species, etc.).

The Fisheries Working Group also recommended that fisheries scientists devote more time to collaborating with scientists in other disciplines (e.g., physical oceanography) to develop ecosystem models that would include factors such as effects of nutrient loading, natural events such as storms, habitat loss and degradation, as well as harvesting on individual species and groups of species. This is the only productive way to provide insights into the relative effects of human activities versus natural events and processes on ecosystem structure and function in the Gulf of Maine.

This Working Group also considered some scientific questions and issues that are related to the enhancement of depleted wild stocks, in this case cod stocks in the Gulf of Maine. In Maine, this would involve the release of hatchery-raised juveniles into nearshore habitat that used to support populations of spawning cod.

These issues are the following:
1. Success of enhancement experiments needs to be monitored, in the short term by following survival, growth, and dispersion of released juveniles and, in the long term, by determining the degree to which targeted spawning populations recover;
2. Sites where juveniles are released should be protected from harvesting practices that will remove or disturb released fish and the size of these "refuges" should be determined based on what is known about the carrying capacity of the environment for juvenile cod; and
3. Release sites should be selected based on known habitat requirements (food, substrate, depth, bottom temperature, etc.) for juvenile cod.

Aquaculture

Ken Waiwood

Aquaculture is an emerging industry in the Gulf of Maine and its representation within the research forum will undoubtedly grow. Most of the aquaculture-related comments by the management panelists, and indeed many of the papers presented at this meeting, addressed the potentially negative impacts of this activity on the ecosystem. A notable exception was the plenary address by Dr. Joseph Brown which summarized the current status and economic potential of this industry in the Gulf of Maine. The aquaculture subgroup noted that if aquaculture is to realize its full potential, it will require greater input from, and more research in, various disciplines. This includes an improved ability to select sites based on appropriate physical and ecological characteristics. This would maximize return on investment and minimize negative environmental impacts. The need to identify a series of variables which could be used to determine suitability and to develop predictive models were identified as priority issues for the industry.

Not surprisingly, many environmental factors which affect wild populations are also of concern to aquaculturalists. These include the distribution and dynamics of harmful algal populations, and watershed issues including bacterial contamination, inorganic and organic contaminants and industrial effluents. The potential introduction of diseases and parasites from wild populations was another concern.

Given the small footprint of aquaculture in the Gulf of Maine, negative environmental impacts tend to be localized. However, these are important and the aquaculture subgroup identified several high priority areas where more research is required. These include nutrient loading and the accompanying decrease in species diversity under cage sites, monitoring and defining monitoring criteria and intervention points, and the potentially negative impacts of chemotherapeutants for the treatment of disease, parasites and fouling organisms. The industry would benefit from improved prediction of dispersion. Also important, but of lower priority, were potentially negative effects of escapees (genetic contamination and disease introduction), and negative interactions with mammals and birds.

The final area addressed was fishery/aquaculture interactions. These could be negative as in the case of conflicts for sites or space, competition for wild juveniles (e.g., sea urchins), or the re-suspension of particles by trawling activities. Because aquaculture is the more recent activity, many regulators view conflicts from the traditional fishery perspective. Methods for resolving conflicts must be less biased and consider only the relative impacts/importance of both activities on environmental, economic and social issues. On the positive side, it was noted that production of juveniles for enhancement and culture utilize identical technology and much could be gained from cooperation.

Aquaculture must be integrated into other areas of research and take a team approach to solving problems. One way to foster interdisciplinary research would be to develop specific models to resolve issues related to site selection, estimation of carrying capacity and environmental impact. A modeling approach could also be used as a decision-making tool to resolve fishery/aquaculture conflicts. It was also felt that by identifying specific geographical areas for interdisciplinary research such as Cobscook Bay or Passamaquoddy Bay, more could be learned about ecological factors affecting aquaculture and the impact of this activity on the ecosystem.

Poster Session Abstracts

Simulation of Outfall Plume Characteristics Using a Far Field Circulation Model

Xueyong Zhang
Moffatt and Nichol Engineers, 250 West Wardlow Rd., Long Beach, CA 90807 310-426-9551

E. Eric Adams
MIT 48-325, Cambridge, MA 02139
617-253-6595 eeadams@mit.edu

Recently several applications have been reported where large 3-D numerical models have been used to predict changes in coastal water quality associated with the construction or relocation of a sewage outfall, such as that for the city of Boston. These "far field" models typically compute advective and diffusive transport—as well as physical, biological and chemical transformation processes—over domains extending 10s to 100s of kilometers using grid sizes of 100s to 1000s of meters. By contrast, outfall mixing occurs at much smaller scales on the order of meters and is usually handled by an initial mixing or "near field" model. Because of this large scale disparity, it is of interest to compare the predictive capabilities of these two model types and to identify ways in which they could be coupled. Extensive comparisons (Zhang and Adams, 1996) of model predictions with a 3-D circulation model (ECOMsi) and an initial mixing model (EPA's RSB) suggest that the former does a reasonable job of predicting plume trap height and dilution, but often overpredicts plume width. As expected, the results are sensitive to the level of discretization and the parameterization of horizontal and vertical diffusion. Major reasons for the apparent success include the fact that initial dilution is partially governed by gravitational exchange flow (a large scale phenomenon which the model can resolve) in addition to plume entrainment (which is clearly sub-grid scale), as well as the self-regulating relationship between plume trap height and inital dilution. Meanwhile the overprediction of plume width is attributed to numerical diffusive effects. Several procedures for improving predictions by coupling near and far field models have been explored, ranging from the use of the near field model to dynamically adjust far field mixing parameters so that the far field model simulates the correct trap height, to simply using the near field to assign source location and dimension for the far field.

(Key Words: initial mixing, sewage, outfall, circulation, trap height)

Current Efforts to Enhance Cod Stocks in the Gulf of Maine

Ted Ames
P.O. Box 188, Stonington, ME 04681
207-367-5907

The collapse of groundfish stocks in the Gulf of Maine has generated new interest in ways to restore wild stocks of fish. A committee was formed in 1993 by the Maine Legislature to study the use of hatchery-

reared fish to revive inshore stocks of cod and haddock along Maine's coast. The committee concluded that, while release of hatchery fish on a put-and-take basis would not be practicable, using hatchery production to create new spawning populations in selected areas could revitalize local populations.

During the past two years, a survey of historical cod and haddock spawning grounds from Grand Manan Channel to Ipswich Bay has been completed. Habitat mapping to identify appropriate release sites within those areas has been initiated to characterize substrate and water column properties.

Two hatcheries have been established; one using a recirculating system and the other, using a flow-through system. Post-larval cod have been successfully grown in both hatcheries, and quantities have been released in selected areas along Maine's coast.

An analysis is made of the current restocking effort as a strategy for stock enhancement. The question of whether depleted wild stocks of cod and haddock in the Gulf of Maine can be enhanced by hatchery-grown fish is examined. Scientific issues that must be addressed before enhancement can become a practical management tool are explored.

Eelgrass Bed Mapping in Coastal MaineWaters

Seth L. Barker
Maine Department of Marine Resources, P.O. Box 8, West Boothbay Harbor, Maine 04575
207-633-9307 mrsbark@state.me.us

An effort has been underway for the past three years to map the location and density of eelgrass along the coast of Maine. The objectives are to better understand the present day distribution of eelgrass beds and to identify sensitive areas along the coast for protection in the case of an oil spill.

The mapping is being done from 1:12000 metric quality photography which were acquired following NOAA C-CAP protocol for aerial photography of SRV (Submerged Rooted Vegetation). Maps generated are stored in a GIS format and field verification is carried out with the aid of GPS.

This poster will present the status of this work and will highlight some of the methodologies used for mapping and field verification. It will serve to demonstrate the advantages of using GIS to integrate all phases of this work.

(Key Words: Gulf of Maine, mapping, eel grass, GIS)

Geographic Information Systems and a New Approach to Mapping Marine Environments on the Maine Inner Continental Shelf

Walter A. Barnhardt, Daniel F. Belknap
Dept. of Geological Sciences, University of Maine, Orono, ME 04469
207-581-2155 walterb@raven.spatial.maine.edu

Joseph T. Kelley, Stephen M. Dickson
Maine Geological Survey, 22 State House Station, Augusta, ME, 04333-0022
jkelley@maine.maine.edu

The bedrock-framed seafloor of the Maine inner continental shelf is characterized by extreme changes in bathymetric relief, and covered with a wide variety of surficial materials. Traditional mapping techniques, based solely on bathymetry and bottom samples, or computer-generated images of acoustic reflectance cannot accurately represent the great heterogeneity of such a glaciated region. Our new method of mapping complex seafloors, based primarily on the interpretation of side-scan sonar, utilizes four easily recognized units: rock, gravel, sand and mud. In many places, however, the seafloor exhibits a complicated mixture or extremely 'patchy' distribution of the four basic units, which are too small to map individually. Twelve composite units, each a two-component mixture of the basic units, were established to represent this patchiness at a small scale (1:100,000). Using a geographic information system, these and all other available data (seismic profiles, grab samples, sub dives and cores) were referenced to a common geographic base, superimposed on bathymetric contours and then integrated into surficial geologic maps.

Approximately 12% of the 9,995 km^2 study area was directly imaged by side-scan sonar. In other areas bottom types were extrapolated on the basis of bathymetry, seismic data, bottom samples and submersible observations. Rock comprises the dominant substrate in the region (4080 km^2, 41% of study area), especially in

depths less than 60 m. Mud (3850 km^2, 39%) occupies deeper basins offshore and sheltered estuarine areas, where it is often charged with natural gas. Large deposits of sand (824 km^2, 8%) and gravel (1240 km^2, 12%) are concentrated seaward of major rivers and in areas of eroding glacial deposits, although small accumulations of biogenic shell material locally occur. These compilations of interpreted geologic observations, rather than automated maps of raw data, are most useful to scientists who need to understand the seafloor but lack experience interpreting geophysical records. Soon available in digital format (CD-ROM or internet) and coupled with viewing software, this new generation of maps will allow researchers to formulate sophisticated queries and perform detailed analysis of seafloor environments.

(Key Words: Maine inner continental shelf, seafloor mapping, marine habitats, geographic information systems).

Phosphorus Cycling and Export Production in the Gulf Of Maine: A Multi-Tracer Approach

Claudia R. Benitez-Nelson, Ken O. Buesseler
Marine Chemistry and Geochemistry,
Woods Hole Oceanographic Institution,
266 Woods Hole Road, Woods Hole, MA 02543
claudia@athena.mit.edu, kbuesseler@whoi.edu

A new approach is proposed to quantify the uptake, regeneration and export rates of phosphorus in the Gulf of Maine. More specifically, a suite of naturally occurring radionuclides will be measured to directly trace the *in situ* turnover rates of phosphorus (using cosmogenic 32P and 33P), upper ocean mixing rates (using 7Be), and surface export fluxes of particulate matter (using 234Th). Preliminary results will be presented from samples obtained from Wilkinson Basin during early July, 1996. Significant advances have been made in the radiochemistry of phosphorus isotopes allowing for the measurement of both 32P and 33P in several biologically relevant P pools. This is possible due to improved methods of sample preparation and new measurement techniques involving low level liquid scintillation counting.

We will use this data to quantify the *in situ* nutrient turnover rates over the mean-life of the P isotopes. This will have a tremendous impact on furthering current understanding of the biological pools active in nutrient uptake and regeneration. Phosphorus isotopes are advantageous in that phosphorus is directly utilized by organisms and the half-lives of 32P and 33P (14.3 and 25.3 days, respectively) are short enough to follow biologically driven processes. Thus, our integrated tracer results will further increase present understanding of the processes which contribute to the temporal and spatial variability of nutrient turnover and export production in the Gulf of Maine.

(Key Words: Gulf of Maine, phosphorus, export production, 32P, 33P, 7Be, 234Th, vertical eddy diffusivity).

An Investigation of the Nutrient Dynamics of Jeffreys Basin: A Potential Nutrient Trap

Heather Benway, Theodore Loder III
Estuarine/Coastal Chemistry Laboratory, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH 03824 U.S.A.
603-862-1542 hmbenway@christa.unh.edu

Jeffreys Basin is located in the southwestern Gulf of Maine just northeast of Cape Ann. The basin has a maximum depth of ~150 m and is partially enclosed by Jeffreys Ledge, which is ~50 m deep.

River input forms a productive coastal plume in the western Gulf of Maine, which contributes a great deal of biogenic material to the water column. This biogenic material is remineralized as it settles downward, thus causing relatively high dissolved inorganic nutrient concentrations in the deeper waters of Jeffreys Basin. Vertical stratification from late spring to early fall limits the water column's capacity for vertical mixing, which inhibits the return of the regenerated inorganic nutrients to the surface. Furthermore, the partial enclosure of Jeffreys Basin by Jeffreys Ledge reduces the periodic flushing of the basin's bottom waters. A combination of these processes may lead to the seasonal accumulation of nutrients in the bottom waters of Jeffreys Basin.

Townsend and Christensen (1992) observed high nitrate concentrations in Jeffreys Basin bottom waters during the biologically productive months (late spring-early fall). During the winter, this region exhibited the highest surface water nitrate concentrations in the entire

Gulf of Maine due to convective overturn of these nutrient-rich bottom waters. Donoghue (1993) also observed very high silicate concentrations in Jeffreys and Wilkinson Basins during the fall of 1987.

Several data sets are being used to examine the nutrient dynamics associated with this region. Two hydrographic surveys were conducted in the southwestern Gulf of Maine in May and October 1995. Water samples were collected and analyzed for NO3, NO2, NH4, PO4, and SiO4, and temperature and salinity (vs. depth) profiles were obtained for each station. Using these and various other data sets from this region, several analyses will be performed in order to determine the patterns of nutrient cycling and how this cycling is coupled to physical processes.

(Key Words: Jeffreys Basin, nutrient, coastal plume, remineralization, seasonal accumulation).

The Decrease of Metal Concentrations in Surface Sediments of Boston Harbor

M.H. Bothner, M. Buchholtz ten Brink, F.T. Manheim
U.S.G.S. Woods Hole, MA 02543
508-457-2240 mbothner@usgs.gov

The concentrations of metals in surface sediments of Boston Harbor have decreased during the period 1977-1993. This conclusion is supported by analysis of:
1) surface sediments collected at monitoring stations between 1977 and 1993;
2) metal concentration profiles in sediment cores from depositional areas of the harbor; and
3) historical data from a contaminated-sediment database which includes information on metal and organic contaminants and sediment texture.

The background and matrix-corrected concen-trations of lead (Pb) measured in the surficial layer (0-2 cm) of cores decreased by an average of 46% q 9% among four locations in the outer harbor during the 16 year period. Chromium (Cr), copper (Cu), mercury (Hg), silver (Ag), and zinc (Zn) exhibited similar trends.

Results from this study are supported by analysis of all data generated from diverse sources during the last 22 years. A sediment database for the region contains approximately 3000 samples; of these, about 600 samples have been analyzed for Cu, Hg, Pb, and Zn in surface sediments. Concentrations of Cu, Hg and Zn decreased with time in the Inner Harbor and outer harbor (Northwest area) surface sediments, however, Pb showed little change. The concentrations of metals within each year-class in the database are highly variable. In the case of the Inner Harbor, the reduction in this variability and average contaminant concentration with time appears to reflect a reduction in industrial and other point sources during the 1970's after the U.S. EPA NPDES discharge permit system was established. Observed decreases in metal concentrations in both Inner Harbor and outer harbor areas in more recent years are attributed to source reductions, such as:
1) ending of sewage sludge discharge to the Harbor in December, 1991;
2) greater recovery of metals by industry (e.g., silver from photographic processing);
3) improvements in wastewater handling and sewage treatment; and
4) diminishing use of lead in gasoline beginning about 1973.

Despite the general decrease in metal concentrations in Boston Harbor surface sediments by 1993, the concentrations of Cr, Pb, and Ag at some stations in the outer harbor were still at, or above, the "medium toxic effects" level (Cr 145 ppm; Pb 110 ppm; Ag 2.2 ppm) of Long and Morgan, 1990.

(Key Words: Boston Harbor, metals, contaminated sediments, cores, sediment database)

Seasonal Changes in Nutrients and Nutrient Ratios in Massachusetts Bay During 1995

Theodore Loder III, **Robert Boudrow**, Cathy Coniaris, Heather Benway, Caroline Martorano
Estuarine/Coastal Chemistry Laboratory,
Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824
603-862-3151 t.loder@unh.edu

As part of the Massachusetts Water Resource Authority's ongoing monitoring program in Massachusetts Bays, 17 cruises were conducted during 1995 from February to December. Eleven of these cruises (Nearfield cruises) focused on the immediate area surrounding the soon to be completed offshore sewage outfall. Six cruises included the above Nearfield area as well as Farfield areas throughout the Massachusetts Bays region from just south of Cape Ann, to Stellwagen Bank and into Cape Cod Bay. On all these cruises numerous physical, chemical, and biological parameters were collected. The data presented here focuses only on the seasonal changes in nutrients (incl. nitrate, nitrite, ammonium, phosphate, silicate) and the N:P and N:Si ratios, mainly in the Nearfield region.

Although there was considerable variability in the averaged surface values, they diverged from the mid and bottom values during the March period and converged in early November at a lower concentration after fall vertical mixing had occurred. These general trends were similar for all dissolved nutrients. However, there were some differences between the nutrients. For example, minimum bottom water values for silicate were in late February, in mid-May for nitrate+nitrite and phosphate, and in December for ammonium. Differential rates of nutrient regeneration in the bottom waters caused early winter concentrations to be higher for nitrate+nitrite and phosphate, but lower for silicate. Dissolved inorganic nitrogen (DIN - nitrate + nitrite + ammonium) to phosphorus ratios (DIN/P) showed that both surface and bottom waters were much lower than Redfield ratios of 16:1, ranging from =8912:1 during the winter to =891-4:1 during the summer months. This suggests that these waters are depleted in nitrogen relative to phosphorus throughout the whole year. The DIN:Si ratios remained between 0.2 to 2 throughout almost the entire year with higher values during the winter and low values during the late spring and summer, reflecting the impact of early spring diatom blooms and slow return of dissolved silicate to the water column.

(Key Words: Massachusetts Bays, nutrient, nutrient ratios, seasonal trends, MWRA)

Prehistoric Cultural Responses to Changes in the Gulf of Maine

Bruce J. Bourque
Bates College, Lewiston, ME, 04240, and the Maine State Museum, Augusta, ME 04333
207-786-6080 bbourque@abacus.bates.edu

Daniel F. Belknap
Department of Geological Science, University of Maine, Orono, ME, 04473

Detmar Schnitker
Darling Marine Center, University of Maine
Walpole, ME, 04573

The Gulf of Maine has undergone dramatic change during the Late Pleistocene and early Holocene, much of it caused by fluctuation in relative sea level. After a low stand of about 60 m below its modern level at about 11,000 B.P., sea level rose rapidly to -20 m at about 9500 B.P., slowed until 7000 B.P., resumed a rapid rate of rise to -5 m at 5000 B.P., then slowed progressively into the historical era, with a distinct deceleration at about 2000 B.P. These sea-level changes have affected the composition and distribution of water in the Gulf, which in turn has determined its biological productivity. The rise allowed penetration of relatively warm and very salty offshore waters along with associated species from areas south of Cape Cod. About 5000 B.P., diatom flora and benthic foraminifera became completely modern, with the species *Bolivina subaenariensis* dominating the foraminifers. This association of flora and fauna indicates the arrival of a very high tidal regime which caused upwelling of deep nutrient-rich waters to the surface, where photosynthetic algae consumed them to form the bottom of a highly productive food web which persists to the present. Associated with these changes were slight declines in temperature and salinity. Eventually, about 2000 B.P., the Gulf became too large for the perfect tidal resonance which had caused the extremely high tides, and the Gulf attained its modern state. In combination with apparently rapid climatic cooling after about 4500 B.P., marine environmental changes of this magnitude appear to have had a noticeable impact upon the human occupants of the Gulf shore. Using archaeological and paleontological data as well as light stable isotopes in human bone, we have explored the affects of sea-level rise on these prehistoric populations, especially those of Penobscot Bay, during

the past 6000 years. The clearest candidate for such environmentally-induced cultural change is the sudden cessation of swordfishing around 3800 B.P., and the disappearance of the distinctive maritime hunting culture that depended upon this species. Swordfish are warm water dwellers only occasionally seen along the Maine coast today. The prevalence of their remains in sites dating prior to this time, however, suggests that formerly their populations were high. This abundance reinforces the hypothesis that the water temperatures in the Gulf were warmer, at least during the summer, before the advent of extreme tidal mixing. At the Turner Farm site, on North Haven, Maine, the cultural disconformity dating to this period was also accompanied by the disappearance of *Mercenaria mercenaria*, another indicator of warmer-than-modern sea-water temperatures.

(Key Words: archeology, sea-level change, diatom flora,swordfish, water temperature, benthic foraminifera)

Modeling The Circulation in Cobscook Bay: A Status Report

David A. Brooks, Yao-Tsai Lo
Department of Oceanography, Texas A&M University, College Station, TX 77843
409-845-5527 dbrooks@cobscook.tamu.edu

Cobscook Bay experiences tidal ranges exceeding 8 m at springs, with tidal currents greater than 3 m/s in narrow straits and between islands. The bay has a complex multibranched coastal topography, with fresh water inflow from several rivers. Tidal stirring keeps the waters cold in the summer and warmer than would otherwise be expected in the winter. The strong currents bring nutrients into the bay from the waters of the Gulf of Maine offshore. The bay is known for its high productivity, its pristine state, and for an extraordinary diversity of marine invertebrates, waterfowl and shorebirds, including many bald eagles. In the last decade a major salmon aquaculture industry has been established in the bay.

As part of an ecosystem study of Cobscook Bay, we are using the Blumberg and Mellor sigma-coordinate numerical model to simulate the tidal and nontidal circulation resulting from forcing by the tides, river runoff, and the wind. The model is initialized with temperature and salinity data obtained from six cruises during 1995, augmented with historical data. The field data also include nutrient, chlorophyll and bottom sediment samples, which can be used to calculate fluxes across critical sections. The model simulations produce tidal elevations and current distributions that are generally consistent with local experience in the bay. Tidal mixing plays an important role in exchange between the bay and offshore waters, but it does not totally overcome the stratification resulting from fresh water sources. The simulations also indicate that a persistent residual eddy pattern in the central arm of the bay may affect the way pollutants are flushed from the bay and nutrients are brought into the inner parts of the bay. Residence times, calculated from model velocity fields over multiples of tidal cycles, range from less than one tidal cycle (half a lunar day) to more than eight days (sixteen semidiurnal tidal cycles), with surprising "patchiness" in the distribution of residence time. For example, particles released in two adjacent grid cells located near the entrance to the bay follow very different paths as they move through the bay under the influence of the tidal currents: one particle leaves the bay after a few days, but the other, which was released on the rising flood only about 200 m distant from the first, became trapped in the inner bay and remained there for the duration of the eight-day experiment. The residence-time experiments suggest that flushing of pollutants from the bay sensitively depends on the location of initial release of the pollutant and the timing of release within the tidal cycle. These and other results from the circulation model will be used in an ecosystem model, which we expect will further understanding of the critical factors responsible for the bay's rich biological diversity.

(Key Words: circulation, ecosystem, tidal, mixing, dispersion, Cobscook)

A Pair of Complementary Marine Data and Information Management Systems for the Gulf of Maine

Wendell S. Brown, Karen M. Garrison
Ocean Process Analysis Laboratory, Morse Hall,
University of New Hampshire, Durham, NH 03824
603-862-3153 wsbrown@kelvin.unh.edu

A Research Environmental Data Information System (REDIMS) is being developed by researchers at the University of New Hampshire, Dartmouth College, U.S. Geological Survey, Woods Hole Oceanographic Institution and Bedford Institute of Oceanography primarily for use by the Regional Marine Research Program (RMRP) researchers and other interested users in the northeast region including the Gulf of Maine. REDIMS (http://opal-www.unh.edu/redims.html) is patterned after the Gulf of Maine Council on the Marine Environment's (CME) Environmental Data and Information Management System (EDIMS; http://opal-www unh.edu/edims.html). EDIMS is being developed primarily for the CME and the marine resource management and protection community.

Both systems provide access to information/data which is physically stored at sites distributed throughout the community. Because they reside on the Internet and are accessed via a Web browser (eg. Netscape), exchange of electronic information/data is relatively easy. Both systems use the same Master Address List from which users can generate their own particular subdirectory address list through a choice of keywords. The Database Directory is another REDIMS/EDIMS shared directory which includes information on 150 marine-related databases for the region. "Data Providers" will be able to update Database Directory information and PRODUCE subdirectories via a system much like that used for the Master Address List.

The Document Libraries on REDIMS and EDIMS contain specialized reports particularly relevant to the particular community being served. Different suites of Electronic Environmental Data are highlighted on REDIMS and EDIMS. On EDIMS we have federal operational data including NOAA National Data Buoy Center near-realtime ocean buoy and island station meteorological data, NOAA/National Ocean Service (NOS) and Canadian Marine Environmental Data Service (MEDS) archived hourly coastal sea levels, New Brunswick daily river discharges, and NOAA's Coastwatch satellite infrared Sea Surface Temperature (SST) images. REDIMS can highlights research data sets including RMRP moored time series, hydrography, assorted biogeochemical constituents and model results. REDIMS also employs the JGOFS data management system, the beginnings of a system which enables researchers and managers to synthesize a diverse range of information for many purposes.

(Key Words: data management, research data, environmental data, directories, data archive)

On the Wind-Forced Response of the Western Gulf of Maine Coastal Ocean

H. Feng, **Wendell S. Brown**
Ocean Process Analysis Laboratory, Morse Hall,
University of New Hampshire, Durham, NH 03824
603-862-3153 wsbrown@kelvin.unh.edu

A joint University of New Hampshire (UNH)/U.S. Geological Survey (USGS) field measurement program, conducted during the spring and summer 1994, consisted of a moored array along an across-shore transect between Cape Porpoise, ME and the center of Wilkinson Basin. Hydrographic measurements clearly document the transition from salinity-controlled stratification in April to the much stronger temperature-induced stratification in August. The obvious seasonality in the relevant stratification field prompted us to subdivide all of the time series into SPRING (1 April to 19 May) and SUMMER (18 July to 4 September) segments.

The mean windstress over the Gulf was generally northeastward and uniform spatially in both SPRING and SUMMER. The windstress fluctuation energy had Gulf spatial scales was concentrated in the 2 to 15 day period "weatherband" and was about four times larger in SPRING than in SUMMER. Also the SPRING windstress fluctuations were also more isotropic than SUMMER windstress fluctuations, which were strongly polarized in the north/south direction and had weaker east-west winds throughout the Gulf.

Observed across-shore pressure gradient fluctuations (related to wind-forced alongshore geostrophic transports) shoreward of the 100m isobath were generally more energetic than those in the interior Gulf.

Surprizingly the coastal across-shore pressure gradient (alongshore flow) fluctuations were more energetic in SUMMER than in SPRING. In both SPRING and SUMMER, the mean surface currents (order 10cm/s) were both stronger and distinctly more offshore than the deeper currents which were more alongshore. The wind-forced alongshore fluctuating currents were sheared like the mean currents and of similar magnitude. The wind-forced across-shore fluctuating currents exhibited a robust Ekman transport near the surface. Conceptual models of the wind-forced response in SPRING and SUMMER have been constructed. SPRING: Springtime wind fluctuations are nearly isotropic with equal amounts of energy in all directions. However the Gulf responds most robustly to east-west winds. Increased eastward windstress lowers Gulf-scale sealevel quickly by exporting water southward out of the Gulf in the surface Ekman layer. The alongshore component of this eastward wind-forcing produces upwelling-fed Ekman transport in the surface layer. A compensation flow enters the Gulf at depth, eventually becoming a coastally-intensified current flowing clockwise around the rim of the Gulf towards the northeast. This wind-driven current, which opposes the seasonal mean coastal current (sometimes reversing it), takes about 2 days to develop fully at Cape Porpoise. SUMMER: Summertime wind fluctuations are less energetic and have alongshore windstress pulse quickly produces a surface alongshelf current in associated Ekman transport, the windstress-forcing also quickly establishes an Gulf-scale alongshelf pressure gradient force which opposes the windstress. In respose, a subsurface flow counter to the wind is setup off of Cape Porpoise after about a day.

Inverse Model-Derived Advective and Diffusive Flows in the Gulf of Maine Region

Frank L Bub, Wendell S Brown
University of New Hampshire, Morse Hall
, Durham, NH 03824, USA; 603-862-3154
frankb@kelvin.sr.unh.edu

A forty-eight element box model has been developed for the Gulf of Maine region including the Scotian Shelf and Georges Bank. The twelve subregions delineate the basin / bank geography of the region. Density surfaces separate four layers which roughly correspond to Maine Surface, Intermediate, Bottom and Deep (e.g., Atlantic Slope) Water masses. Objective analysis (OA) techniques are used to interpolate monthly climatologies of the extensive Atlantic Fisheries Adjustment Program (AFAP) hydrography onto the seven km Greenberg model grid. Layer thicknesses and spatially averaged temperature, salinity and density distributions are derived from the gridded data. Temperature-salinity relationships demonstrate the disappearance of the low-density surface layer during winter and its reconstruction and stratification during summer. February vertical sections show isopycnal connections between the deep Wilkinson Basin and Georges Bank via the bottom and intermediate layers. These are potentially "easy" pathways for the movement of Calanus finmarchicus onto the Bank after overwintering at the bottom of the Basin—a key hypothesis in the GLOBEC study.

The inverse model, consisting of finite difference statements of conservation of volume, temperature and salinity, represents a system 144 equations with 300 unknowns. The model is solved for advective and eddy transports using singular value decomposition (SVD). An initial series of steady state experiments has concentrated on the September climatology, when Gulf-wide stratification isolates the surface from deeper layers. The model Gulf of Maine system is forced at the boundaries by various measured and inferred transports. For example, a run with a flow of 0.5 Sv (10^6 m^3/s) across the Scotian Shelf, the Northeast Channel closed, and Nantucket Shoal open produces an intermediate layer cyclonic gyre of 0.3 Sv across Jordan and Wilkinson Basins, accompanied by a southwestward Maine Coastal Current and cross-channel flow between the Shelf and Georges Bank. With a goal of describing the climatological annual evolution of flow and mixing processes, model results will be presented from months when Gulf surface forcing due to heat and freshwater exchanges are important. The uncertainties which come from SVD can be compared with OA error fields and provide important insights into the derived flows. The possibility of using conservative zooplankton genes to reduce the systems underdeterminancy will also be studied.

(Key Words: Gulf of Maine, circulation, inverse modeling, climatology, advective transport)

Contaminated-Sediment Database for the Gulf of Maine

Marilyn Buchholtz ten Brink,
Frank T. Manheim, Polly Hastings
The Northeast Marine and Coastal Geology Center of U.S. Geological Survey, Woods Hole, MA, 02543
508-548-8700 mtenbrin@usgs.gov

Stephen H. Jones, Larry G. Ward
Jackson Estuarine Laboratory of the University of New Hampshire, 85 Adams Point Rd., Durham, NH, 03824 603-862-2175

Peter F. Larsen
Bigelow Laboratory for Ocean Sciences, PO Box 475, McKown Point, West Boothbay Harbor, ME, 04575
207-633-9600

Bruce W. Tripp, John W. Farrington
Woods Hole Oceanographic Institution, Quissett Campus, Woods Hole, MA, 02543 508-548-1400

Gordon T. Wallace, Jr.
Dept. of Environmental Sciences, University of Massachusetts-Boston, 100 Morrisey Blvd., Boston, MA, 02125 617-287-7447

A database of existing data on chemical contaminant concentrations in sediment for the Gulf of Maine region has been compiled with the collaboration and cooperation of many scientists, agencies, and institutions. The database contains 1) original data on chemical constituents and sample identification from published and gray literature sources, and 2) documentation about the quality of the data. Over 6200 sediment samples (collected primarily by corer and grab samplers) are listed. The heterogeneity of the data sources resulted in differing degrees of certainty in the data; however, scientific editing identified problems and allowed many of them to be repaired or qualified for future data users. The concentrations of metal and organic contaminants are being used to create maps of contaminant distributions in the region and investigate transport processes. Sample density is not uniform in the Gulf of Maine. Samples are concentrated in urban, coastal locations and targeted study areas, such as U.S.-EPA designated National Estuaries. Concentrations of metal contaminants in surface sediments range from background to three orders of magnitude above natural values. The highest contaminant values in surface sediments are located near urban areas, with a halo of elevated values around them. The patchy distribution of contaminant concentrations for bulk sediments throughout the Gulf of Maine reflects patchiness in both contaminant sources and sedimentary regimes. The database is a growing document that can be used by persons throughout the region for scientific and management purposes.

(Key Words: contaminants, sediment, database, metals, organics, pollution)

Changes in the Fish Community of Plum Island Sound, Massachusetts from 1967 Through 1994

Robert Buchsbaum
Massachusetts Audubon Society, Wenham, MA 01984
508-927-1122 rbuchsbaum@massaudubon.org

Linda Deegan, Robert Garritt
The Ecosystem Center, Woods Hole, MA,02543
508-548-3705
ldeegan@lupine.mbl.edu hgarritt@lupine.mbl.edu

In 1965 the Massachusetts Division of Marine Fisheries (DMF) surveyed fish within Plum Island Sound, a shallow estuary in the southern part of the Gulf of Maine, at monthly intervals over a period of one year. The existence of this historical data set provided us with an opportunity to examine changes over time in the fish community within the Sound. Over a 16 month period in 1993-1994, we revisited the exact same stations as those sampled in the DMF study and used very similar methods (beach seine and otter trawl). From a methodological perspective, the beach seining stations provide the most reliable comparisons. We found higher abundance of individuals and greater species richness in 1993-4 compared to the 1965 study, both overall and in most individual sampling stations. The two most abundant species we collected, Atlantic silversides (*Menidia menidia*) and mummichog (*Fundulus heteroclitus*) account for greater than 90 percent of the individuals and biomass in our samples. Although silversides and mummichogs were also the two numerical dominants in the DMF study, they were about ten and five fold higher in population in 1993-4 than in 1965. They presently make up a much larger percentage of the catch than in the past. There were no obvious patterns in other species of fish. We suspect that the tremendous increase in the two major species of "bait fish" are a

result of regional trends that are not specific to Plum Island Sound, since the Sound itself and its surrounding watershed has remained relatively undeveloped over the past thirty years.

(Key Words: estuarine fish, historical change, Plum Island Sound)

Measuring Water Constituents in the Gulf of Maine: Exploring Future Ocean Color Algorithms Based on Spectral Radiance Models

Janet W. Campbell, Tom Krasuski
Ocean Process Analysis Laboratory, University of New Hampshire, Durham, New Hampshire 03824
603-862-1070 campbell@kelvin.sr.unh.edu

A spectral radiance model relates the upwelled radiance emerging from the water surface to the concentrations of water constituents that affect water color. These constituents include phytoplankton pigments, colored dissolved organic matter, and suspended sediments. For every spectral band measured by a satellite sensor, there is a nonlinear equation describing the dependence of upwelled radiance on the constituent concentrations. Future ocean color algorithms will invert the system of equations, one for each spectral band, to estimate a vector of water constituent concentrations at every "pixel" in the satellite image.

In this poster, we will demonstrate this technique using CZCS data from the Gulf of Maine. Three bands of water-leaving radiance will be inverted to produce maps of phytoplankton chlorophyll, CDOM, and suspended particulate matter. Future satellite sensors will have five or more bands from which additional constituents may be determined and/or error estimates made on fewer constituents. A protocol will be described for parameterizing a regional algorithm for the Gulf of Maine.

Differences in Fish Communities Among Nearshore Habitats in Boston Harbor and Northern Massachusetts Bay

Mark Chandler
New England Aquarium, Central Wharf, Boston, MA 02110-3399
617-973-5274 mwc@neaq.org

Phil Colarusso
U.S. EPA; JFK Federal Building; Boston, MA 02203; 617-565-3533 colarusso.phil@epamail.epa.gov

Robert Buchsbaum
Massachusetts Audubon Society; Endicott Regional Center, 346 Grapevine Road; Wenham, MA 01984; 508-927-1122 rbuchsbaum@massaudubon.org

The general consensus that vegetated near-shore habitats such as eelgrass meadows are a significant fish habitat is based primarily on studies done in the Mid-Atlantic. Although early work in Europe and more recent work in Canada suggest that young cod benefit from eelgrass beds, few studies have examined the relative importance of different near shore habitats for fish communities north of Cape Cod. Eelgrass in New England frequently occurs as small patchy beds due to coastal geology, extensive coastal development, wasting disease and poor water clarity. We compared the fish species present in four small eelgrass beds and nearby unvegetated areas in Massachusetts using gill nets and minnow traps from 1993 to 1995. These surveys were complimented by beach seines and diver transects. Stomach content and carbon and nitrogen stable isotope analysis was completed on several fish to understand the food web structure associated with these habitats. We recorded a total of 43 species, 34 within eelgrass and 31 within the unvegetated reference area. Among other results, juveniles (age 1+) of commercially important species, primarily pollack (but also cod and hake) were more frequently caught in eelgrass than in nearby unvegetated sites. A one year sampling of a macroalgal vegetated site suggests that not all vegetated habitats are of equal value to fishes. Analysis of stomach contents of large pelagic fish caught in eelgrass indicated that most of the individuals contained invertebrates or small fish that are predominantly found in eelgrass. The results from this study confirm that not all near shore habitats are of equal value to fishes, and that even small eel-grass beds function as important fish habitat in Massachusetts Bays.

(Key Words: fisheries, nursery, eelgrass, groundfish, nearshore habitat).

Alternative Treatments for Sea Lice on Farmed Salmon in Southwestern New Brunswick

B.D. Chang
Fisheries and Oceans Canada, Biological Station,
St. Andrews, NB, Canada E0G 2X0
506-529-8854 chang@sta.dfo.ca

G. McClelland
Fisheries and Oceans Canada, Halifax Fisheries Research Laboratory, P.O. Box 550,
Halifax, NS, Canada B3J 2S7

L.E. Burridge
Fisheries and Oceans Canada, Biological Station,
St. Andrews, NB, Canada E0G 2X0

W.E. Hogans
Huntsman Marine Science Centre,
St. Andrews, NB, Canada E0G 2X0

S. Lall
Fisheries and Oceans Canada, Halifax Fisheries Research Laboratory, P.O. Box 550,
Halifax, NS, Canada B3J 2S7

B.M. MacKinnon
Department of Biology, University of New Brunswick,
Bag Service 45111, Fredericton, NB, Canada E3B 6E1

F.H. Page, V. Zitko
Fisheries and Oceans Canada, Biological Station,
St. Andrews, NB, Canada E0G 2X0

An outbreak of the sea louse *Lepeophtheirus salmonis* occurred on farmed Atlantic salmon (*Salmo salar*) in southwestern New Brunswick in the fall of 1994. In response to concerns from the aquaculture industry that treatments permitted at the time were either not efficacious or posed a health hazard to the host salmon, Fisheries and Oceans Canada initiated a research project on alternative methods of control, focusing on approaches that showed promise in the relatively short term. These included treatment with the organophosphate azamethiphos (trade name Salmosan), modification of salmon diet, and light traps for elimination of the parasite's free-swimming larval stages. Because of environmental concerns with the use of chemical treatments, preliminary work was conducted on the dispersion of sea louse chemicals in the marine environment. The final component of the project was analytical chemistry which was required to support other elements of the project.

Bath treatments of azamethiphos were 85-90% efficacious against sea lice on farmed salmon. Laboratory sensitivity tests on the effects of azamethiphos on non-target organisms indicated that crustaceans were most susceptible, especially lobsters (*Homarus americanus*). Lobsters were the only animals which died inside the treatment tarpaulin in 24 h field trials, while there was little or no mortality among species (including lobsters) held at various distances from the treatment cage. Preliminary results indicated that the nutritional status of salmon may act to enhance the pathogenic progression of sea lice. Commercial salmon diets were found to contain amounts of iron in excess of the requirement established for Atlantic salmon. Laboratory tests showed that louse larvae were attracted to a light trap, but the trap was less effective than expected. Preliminary studies on the dispersion of sea lice treatment chemicals used hydrogen peroxide, in conjunction with surface drifters and a current meter. The results indicated that this chemical either disperses vertically or is advected downward very quickly; it generally followed the direction of prevailing currents, with little lateral dispersion; dilution was very rapid; and current velocity and direction were extremely variable in the study area. More detailed chemical dispersion studies are proposed for 1996/97.

(Key Words: aquaculture, Atlantic salmon, sea lice, Bay of Fundy)

Particulate Organic Carbon Export Fluxes in the Central Gulf of Maine Estimated From $^{234}TH/^{238}U$ Disequilibria

Matthew A. Charette, S.B. Moran
Graduate School of Oceanography,
University of Rhode Island, Narragansett, RI 02882
401-874-6273   charette@gsosun1.gso.uri.edu

C.H. Pilskaln
Department of Oceanography, University of Maine,
Orono, ME 04469   pilskaln@maine.maine.edu

Studies of the global carbon cycle and climate change require accurate quantification of the export of particulate organic carbon (POC) from surface ocean waters to the sediments. ^{234}Th ($t_{1/2}$=24.1 d) is a naturally occurring isotope that is produced in situ from ^{238}U ($t_{1/2}$=4.47 x 10^9 y) and provides an integrated measure of POC export from the upper ocean on a time scale of 1-100 days. $^{234}Th/^{238}U$ disequilibria due to particle export can be linked empirically to the biogenic particle cycle via measurement of the $POC/^{234}Th_{part}$ ratio. The purpose of this study is to investigate the utility of ^{234}Th as a tracer of POC in continental shelf waters and to compare the results with time-series sediment traps. $^{234}Th/^{238}U$ disequilibria was measured in the central Gulf of Maine during cruises in March, June and September, 1995. A steady-state model of the ^{234}Th activity balance in the upper ~50 m was combined with measurements of $POC/^{234}Th_{part}$ on >53 μm (LPOC) and 1-53 μm (POC) particle size classes. The ^{234}Th-derived total annual P_{POC} (POC + LPOC) export is estimated to be 8 mol C/m^2/y. This result will be compared with that of sediment traps. Using the Suess equation (Suess, 1980), the export flux is 11 mol C/m^2/y for this region. These POC fluxes compare with an annual primary production of 21 mol C/m^2/y and a carbon burial flux of 4 mol C/m^2/y in the Gulf of Maine (Christensen, 1989). These results suggest that $^{234}Th/^{238}U$ disequilibria may be a useful tracer of particulate organic carbon export fluxes in shelf waters.

(Key Words: 234-Thorium, new production, POC export, sediment traps, seasonal study)

Continuous Fluorescence Measurements for High Temporal and Spatial Resolution of Organic Compounds in Marine Systems

Robert F. Chen, Steven M. Rudnick
UMass-Boston, Environmental Sciences Program,
100 Morrissey Blvd., Boston, MA 02125-3393
617-287-7491   chenr@umbsky.cc.umb.edu

In order to better understand biogeochemical processes in marine systems, an effort has been made to obtain high spatial and temporal resolution of a number of environmental parameters and chemical analytes. We have developed a fiber-optic spectrofluorometer capable of in situ, real-time measurements of UV fluorescence of seawater. This system has been deployed in Boston Harbor, Georges Bank, the Mid-Atlantic Bight, and San Diego Bay in order to map dissolved organic carbon (DOC) distributions, detect polycyclic aromatic hydrocarbons (PAH), and monitor fluxes of organic compounds out of contaminated sediments.

Bulk fluorescence (excitation wavelength=337 nm) correlates quite well with DOC and correlates inversely with salinity in estuarine systems such as Boston Harbor, San Diego Bay, and the Mid-Atlantic Bight. Time-resolved fluorescence spectroscopy allows differentiation of the PAH signal from the dominant DOC signal. Continuous measurement of fluorescence are possible resulting in spatial resolution of ~30m. By placing the fluorescence sensor directly in seawater or in an in-line seawater sampler, high resolution fluorescence measurements can be made continuously along ship tracks that agree very well with discrete samples. Real-time measurements allow mapping of plumes, tracking point sources, and following of blooms. High resolution measurements facilitate determinations of DOC fluxes from the MAB, DOC and PAH fluxes out of Boston Harbor, and PAH distributions in contaminated urban harbors.

Fluorescence can also be monitored in a benthic flux chamber to yield high temporal resolution measurements of DOC and PAH fluxes from contaminated sediments to overlying waters. Spectra taken every 5 minutes allows examination into short-term changes due to tidal influence or episodic biological disturbance that is not possible with discrete samples (every 10 hours).

Fluorescence is also more selective than DOC and is thus less prone to sampling artifacts.

This laser-induced fluorescence system has proven to be a reliable, real-time monitoring tool with a whole host of possible applications.

(Key Words: Fluorescence, DOC, in situ, fiber optic, PAH)

Historical Interpretation of Sedimentary Lead Concentrations in Dipper Harbour Salt Marsh, Bay of Fundy

Yolanda T. Clegg, **Gail L. Chmura**
Department of Geography and Centre for Climate and Global Change Research, McGill University, 805 Sherbrooke Street W., Montreal, Quebec, H3A 2K6, Canada
514-398-4111 chmura@felix.geog.mcgill.ca

Studies from the southern and mid-Atlantic coast have shown that the distribution of lead in salt marsh sediments reflects historical trends in atmospheric loading. However there has been limited effort to document these patterns in salt marshes of the Gulf of Maine - Bay of Fundy waters. We have analysed sediments from Dipper Harbour salt marsh which is situated in an undeveloped, forested watershed, 28 km SW of Saint John. Radionuclide and pollen dating were utilized to obtain accretion rates for this marsh. Presently, our temporal resolution is on the order of 10 to 20 yr, but additional studies are being conducted in attempt to increase our resolution to 5 yr. Patterns of lead deposition in the two cores sampled to date are assumed to be representative of the regional history of atmospheric loading. Using the suite of cores collected from Dipper Harbour we will compare the inventory of sedimentary lead to estimates of lead emissions over the last 200 yr. Air trajectory diagrams are used to determine the large potential source area of atmospheric lead.

(Key Words: salt marsh, lead, sediment, historical reconstruction, New Brunswick).

Response of Georges Bank Waters and Larvae to the Passage of a Gulf Stream Warm-Core Ring

James H. Churchill
Woods Hole Oceanographic Institution, Woods Hole, MA 02543
508-289-2807 jchurchill@whoi.edu

James Manning
U.S. National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1097

When considering the recruitment of cod and haddock larvae over Georges Bank, May-June is a critical period. It is during this time that the cod and haddock larval stock is advected along the southern flank of the Bank within a water mass which is undergoing the development of vertical stratification. As part of the Georges Bank GLOBEC program, southern flank waters were subject to intensive physical and biological sampling during May-June 1995. The data reveal two noteworthy phenomenon which appear to have been related to the approach and passage of a Gulf Stream warm-core ring. One was an intrusion of Slope Water observed in advance of the ring. Within the near-bottom layer this extended as far upbank as the 60 m isobath. It appears to have significantly impacted the distribution of cod larvae over the southern flank. Waters of the intrusion were nearly free of larvae, whereas the highest larvae concentrations were seen slightly onbank of the intrusion's edge. The other phenomenon was a narrow westward current at the shelf-slope frontal boundary. As revealed by drifter tracks and shipboard ADCP data, this was a convergent jet with a maximum westward flow in excess of 50 cm/s. Currently, we are comparing the details of these features with model results. A goal is to determine if inclusion of measured stratification within the model significantly improves the data-model comparison.

(Key Words: Gulf Stream Rings, Georges Bank dynamics, larval distribution and advection)

Physical and Biological Processes Controlling Nutrient Dynamics in Cape Cod Bay

Catherine Coniaris, Theodore Loder III
Estuarine/Coastal Chemistry Laboratory, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824
603-862-1542 coniaris@christa.unh.edu

George Gardner, Tracy Villareal
Environmental Sciences Program University of Massachusetts at Boston 100 Morrissey Boulevard, Dorchester, MA 02125

Nutrient distributions in Cape Cod Bay were determined during five hydrographic cruises from August 1993 to December 1994. A deep-well pump, attached to a CTD, pumped seawater at a constant rate into a five-channel Technicon AutoAnalyzer II which measured nitrate+nitrite, nitrite, ammonium, phosphate and silicate. Discrete samples taken from the pumpstream compared well with Niskin bottle samples.

We found that nutrients are concentrated on a seasonal basis in the relatively shallow (20-60 m) bottom waters until the system resets itself with the fall overturn in early November. Maximum concentrations (silicate ca. 30 =B5M, phosphate ca. 1.8 =B5M and nitrate ca. 13 =B5M) occur during the late summer and early fall. Phosphate and silicate concentrations are much higher relative to nearby coastal regions whereas nitrate concentrations are proportionally lower when compared to phosphate and silicate. The mechanism of concentration involves the geostrophic circulation of the Gulf of Maine coastal current which varies in intensity seasonally due to variable freshwater runoff. During the summer months, this current is generally weaker resulting in a longer residence time for waters in Cape Cod Bay. We hypothesize that organic matter, mainly produced by the early spring diatom bloom within Cape Cod Bay, settles to the shallow bottom and is subsequently remineralized during the warm summer months. The released nutrients are then trapped due to vertical stratification and increased residence time. The relatively low nitrate concentrations compared to silicate and phosphate suggest that selective remineralization and/or denitrification are occurring in these waters.

Winter diatom blooms were observed in December and February, particularly in the shallow southeast corner of Cape Cod Bay. The nutrient signal for these blooms was the depletion of nitrogen and silicate relative to phosphorus when compared to other nearby coastal areas. This suggests that low level diatom blooms can occur throughout the winter months in shallow areas of Cape Cod Bay. Groundwater discharge along the coast may contribute significant amounts of nutrients to these blooms.

(Key Words: Cape Cod Bay, nutrient, nutrient trap, diatoms, seasonal circulation).

Predicted Impacts of MWRA's Discharge to the Mass Bay System: Environmental Monitoring Changes the Problem Definition

Michael S. Connor, Michael J. Mickelson, Kenneth E. Keay, Wendy S. Leo
Environmental Quality Dept., Massachusetts Water Resources Authority, Boston, MA
617-241-6507 enquad@world.std.com

Since 1992, the Massachusetts Water Resources Authority (MWRA) has conducted a baseline monitoring program in Massachusetts and Cape Cod Bays in preparation of the completion of a new 780-mgd secondary treatment plant and offshore diffuser system to replace the existing discharges of primary effluent to Boston Harbor. These baseline monitoring data have refined our understanding of the environmental concerns facing the bays system.

Ten years ago, environmental concerns in Massachusetts Bay centered on localized dissolved oxygen depletion caused by the organic loading from sewage effluent, sedimentation impacts on the benthos, and the disease impacts associated with lipophilic, chlorinated organic hydrocarbons. However, these conclusions were based on short-term data collection, back-of-the-envelope modeling, and baseline evaluation of a barely functioning wastewater treatment system.

Due to (1) a better understanding of the oceanographic processes in the bay from dramatic increases in data collection and modeling and (2) improvements in sewage treatment and source control, the localized oxygen, sedimentation, and toxics issues are no longer paramount. Several years of baseline monitoring, and detailed physical oceanographic measurements as part of the National Estuary Program, have allowed us to construct baywide 3-dimensional models of circulation and oxygen dynamics. These studies, and findings by the National Research Council (NRC), have changed the environmental emphasis to the impacts of nutrient discharges to the bay and the effect of these discharges on plankton productivity, farfield oxygen depletion, and the frequency of nuisance algal blooms. MWRA's environmental monitoring has focused our capital engineering priorities towards this improved definition of the environmental problems associated with the discharge of municipal wastewater to Massachusetts Bay.

The Bay of Fundy: What is Changing and Why?

Peter Wells
Environmental Conservation Branch, Environment Canada, Dartmouth, N.S.

Louise White
Marine Environmental Sciences Division, Department of Fisheries and Oceans, Bedford Institute of Oceanography, Dartmouth, N.S.

Jon Percy
Steve Hawboldt
Clean Annapolis River Project, Annapolis Royal, N.S.

Alison Evans
School of Architecture and Planning, Technical University of Nova Scotia, Halifax, N.S.

Mike Brylinsky, Graham Daborn
Acadia Centre for Estuarine Research, Wolfville, N.S.

Peter Hicklin
Environmental Conservation Branch, Environment Canada, Sackville, N.B.

In the last few years, a number of environmental indicators suggest that the Bay of Fundy ecosystem is undergoing changes that are not easily explained on the basis of present scientific knowledge. These include collapses, or extreme population fluctuations of fisheries resources, apparent changes in patterns of sediment distribution or properties, and consequent changes in abundance or feeding behaviour of shorebirds and fish. However, our understanding of the system is insufficient to select between alternative causes. Moreover, new recognition of the role of saltmarshes and seaweeds challenges notions that such habitats and species can be modified or harvested without system-wide consequences for other resource species and wildlife. For these reasons, the Fundy Marine Ecosystem Science Project (FMESP) was initiated in March 1995.

The first activity, was to develop a synopsis of recent Bay of Fundy scientific information in the form of a background paper accompanied by a supporting bibliography of recent scientific literature. Following this, a Bay of Fundy Workshop, primarily involving the scientific community, was held in early 1996 to discuss issues affecting the Bay. The ultimate goals of the Workshop were to seek a consensus on further marine ecosystem scientific research priorities, to identify coastal management and conservation requirements, and map out a plan for timely multi-partner, interdisciplinary research and management initiatives on the Bay.

The second activity, now underway, will establish a multi-partner Action Plan. It will use an ecosystem perspective to define a set of guiding principles and strategies to encourage, integrate and support scientific research, integrated coastal management and community involvement.

Recent Changes in the Sedimentary Regime of the Inner Bay of Fundy

Gordon B. J. Fader
Geological Survey of Canada Atlantic, Bedford Institute of Oceanography, Box 1006, Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-2159 fader@agcrr.bio.ns.ca

John Shaw
Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, T6G 2H4 Canada
401-545-3573 john shaw@ualberta.ca

Recent studies of the marine geology of the inner Bay of Fundy indicate modern changes in sediment dynamics. Multibeam bathymetry depicts an area of large, isolated, sandy, flow-traverse and flow parallel bedforms overlying thin lag gravels. Subsequent surveys with high-resolution sidescan sonars and seismic reflection systems, together with cores and seabed samples, provide stratigraphic information for a three dimensional interpretation of lithology and seabed and subsurface processes. The largest bedforms are isolated transverse sand dunes up to 12 m in height and 0.75 km in length. Scour depressions around the edges of the dunes suggest active erosion of underlying glaciomarine sedi-

ment. Elsewhere, the bed is protected by a lag gravel. Other bedforms, such as sand ribbons, comet marks and megaflutes indicate net sediment transport to the northeast, toward the head of the Bay of Fundy.

The topography of the area is largely controlled by positive relief till features over Triassic sandstone bedrock. Where exposed, the till surfaces appear a large triangular-shaped rises, likely formed by late glacial, sub-ice, high-velocity meltwater flows. Extensive deposits of glaciomarine sediment are thickest in broad depressions on the till surface.

The sandy bedforms are developed over thin lag gravel surfaces which overlie the thick glaciomarine sediments. The lag surfaces formed through erosion of the glaciomarine sediments in response to increased tidal currents in post-glacial time, as the Bay of Fundy approached resonance. In areas where the lag gravels are being eroded, the underlying glaciomarine mud is exhumed and provides fine-grained materials to the water column.

Large areas of flow parallel bioherms, interpreted as mussel beds, are widespread and present unique backscatter and morphological signatures on sidescan sonar data. Scallop fishing marks occur on areas of gravel, but the effect of this activity on the stability of the thin gravel lag is not yet determined.

(Key words: Bay of Fundy, sediment transport, marine geology, multibeam bathymetry, seabed fishing effects)

The Response of a River Plume to Fluctuations in Wind Stress: Idealized Model Simulations

Derek A. Fong
MIT/WHOI Joint Program in Oceanography,
Woods Hole Oceanographic Institution,
Woods Hole, MA 02543
508-289-2814 dfong@whoi.edu

W. Rockwell Geyer
Woods Hole Oceanographic Institution, Woods Hole, MA 02543 rgeyer@whoi.edu

Richard P. Signell
United States Geological Survey,
Woods Hole, MA 02543 rsignell@crusty.er.usgs.gov

An interdisciplinary study is being conducted in the western Gulf of Maine to investigate the freshwater river plume and its relationship to the transport of the toxic algae, *Alexandrium Tamarense*. A major field program was conducted in the spring of 1993 and 1994 to study and map the spatial and temporal patterns of salinity, temperature, currents, nutrients, and algal cell concentrations. The observations suggest that the plume's behavior is strongly influenced by short time-scale fluctuations in wind forcing.

The effects of transient wind events are studied using a three-dimensional numerical model. An idealized model basin is forced with a point source of buoyancy and wind stress varying sinusoidally as a function of time. Model simulations suggest that despite a zero temporal mean in wind stress, sequences of equal and opposite upwelling and downwelling winds broaden and diffuse the plume's structure. The fluctuations between the two types of wind events do not cancel each other due to enhanced mixing during upwelling favorable conditions which irreversibly alter the plume's density distribution. These simulations illustrate that even under conditions such that there is zero mean wind stress, the fluctuations in wind stress can have an important influence on the mean plume conditions due to nonlinear interactions in the density and velocity fields.

(Key Words: Gulf of Maine, numerical modeling, freshwater plumes, mixing processes)

In-Situ Population Dynamics of Calanus Finmarchicus

Wendy Gentleman
Dartmouth College
8000 Cummings Hall, Hanover, NH, 03755
603-646-2685 wendy.gentleman@dartmouth.edu

Daniel R. Lynch
Dartmouth College
8000 Cummings Hall, Hanover, NH, 03755
daniel.r.lynch@dartmouth.edu

Dennis McGillicuddy
Woods Hole Oceanographic Institution,
Woods Hole, MA 02543 dmcgillicuddy@whoi.edu

Cabell Davis
Woods Hole Oceanographic Institution,
Woods Hole, MA 02543 cdavis@whoi.edu

Observational data shows a high degree of seasonal and spatial variability in the large scale mean abundance patterns for some of the species of dominant zooplankton in the Georges Bank/Gulf of Maine region.

The modeling effort in this study explores the extent to which this variability can be explained by the interaction of physical processes with copepod population dynamics. The focus of the present work is the distribution patterns of the copepod *Calanus finmarchicus* for the January-February (JF) and the March-April (MA) bi-monthly periods.

The physical environment is characterized by realistic Georges Bank topography and pre-computed bi-monthly residual flow fields (both Eulerian and Lagrangian). 13 morphologically distinct copepod stages are related through a stage-based population dynamics model that includes temperature-dependent rates for fecundity and molting, and spatially varying mortality rates. Limitations on food availability is approximated by a depth dependence of the development rates. Vertically integrated long term simulations are discussed and compared with historical data.

Results show that physical transport alone is capable of carrying the animals from Jordan and Wilkinson Basins to Georges Bank in the 2-month period from JF to MA. The structure of this resulting on-bank population is dominated by the egg and naupliar stages. This means that high abundances of nauplii are available in the same region as the early cod larvae are found during this bi-monthy period. Simulations also indicate that the Wilkinson Basin population is advected southward into the Great South Channel; a finding not evident in the observational data. This implies the existence of some alternate local mechanism of removal (either higher biological mortality or vertical variability in the flow field). Simulations with reduced development rates were more representative of the patterns of the observational data, suggesting that the off-bank *Calanus finmarchicus* develop more slowly than at the temperature-dependent rates.

(Key Words: Gulf of Maine, copepod, population dynamics, abundance and distribution patterns)

Vertical Mixing in Massachusetts Bay

Rocky Geyer, Jim Ledwell, Brian Connolly
Woods Hole Oceanographic Institution,
Woods Hole, MA 02536
508-289-2868 rgeyer@whoi.edu

Dye studies were performed in Massachusetts Bay to determine the magnitude of vertical and horizontal mixing. One dye release was performed in the summer of 1993 to measure the dispersion rate in the vicinity of the new outfall. Another release was performed in the summer of 1995 near Scituate, to quantify the influence of boundary mixing.

In the 1993 study, Rhodamine dye was injected into the center of the thermocline in two horizontal streaks that formed an "x" near the Boston weather buoy. The vertical and horizontal distributions of dye were monitored for the next four days, using a towed, profiling fluorometer. The vertical diffusion rate was found to be 0.04-0.08 cm^2/s. This compares with an estimate of approximately 0.1 cm^2/s determined from seasonal variations in temperature. The slow rate of vertical mixing indicates that the nutrients within the plume will tend to remain submerged as they transit the Bay, unless upwelling carries them to the surface along the perimeter.

In the 1995 study, Rhodamine dye was injected into the thermocline close to where it intersected the bottom, at approximately 15-m water depth. Again the dye was sampled on successive days to document its horizontal and vertical spreading. The vertical mixing rate was found to range from 0.17 to 0.38 cm^2/s. Large amplitude internal tidal motions were evident in the velocity and density data, and these motions probably played an important role in the vertical mixing. Mixing also appeared to be enhanced by upwelling, which carried the pycnocline water to within 5-m of the water surface. Although the vertical mixing rate was higher near the boundary than in the interior of Massachusetts Bay, the rate was not high enough to indicate that boundary mixing would dominate the cross-isopycnal flux. Nevertheless, the vertical advection and mixing associated with upwelling may be important conduits for transport of nutrients into the near-surface waters.

Effects of Drilling Wastes on Georges Bank Scallop Populations

Donald C. Gordon Jr., Peter J. Cranford,
Charles G. Hannah, John W. Loder,
Timothy G. Milligan, D. K. Muschenheim
Department of Fisheries and Oceans,
Bedford Institute of Oceanography, P.O. Box 1006,
Dartmouth, NS B2Y 4A2, Canada
902-426-3278 dgordon@biome.bio.dfo.ca

In preparation for future deliberations concerning the moratorium on hydrocarbon drilling on Georges Bank which expires in 2000, a series of coordinated interdisciplinary projects is being conducted to assess the potential magnitude of drilling waste effects (especially drilling muds) on the sea scallop (*Placopecten magellanicus*), the most valuable fisheries resource on the Canadian sector. Field studies on the Northeast Peak of Georges Bank have characterized the physical environment as well as the concentration and size distribution of naturally occurring particulate matter, with emphasis on the benthic boundary layer within which scallops obtain their food particles. Laboratory experiments indicate that drilling wastes aggregate quickly in seawater to form large flocs having high settling velocities (mm to cm/sec) suggesting that fine drilling wastes can rapidly reach the seafloor in continental shelf environments. Field observations at the Cohasset and Panuke fields on Sable Island Bank show the presence of flocculated drilling wastes in the benthic boundary layer up to 8 km away from the release point. Laboratory experiments have demonstrated that adult sea scallops have a very low tolerance to the presence of drilling wastes in their diets. A prolonged, intermittent exposure to waste concentrations of a few milligrams per liter or less can reduce growth and in some cases cause mortality. Numerical models are being developed to predict the distribution of drilling wastes released under different environmental conditions. A benthic boundary layer transport model (*bblt*) has been developed which simulates the vertical mixing and horizontal transport of deposited drilling wastes and predicts the area of seabed potentially exposed to drilling waste concentrations known to effect scallop growth and survival. The model is being tested using data from the Cohasset and Panuke fields and in the near future will be used to explore the potential effects on scallops of different drilling scenarios on Georges Bank.

(Key Words: Georges Bank, sea scallops, drilling wastes, impacts, numerical modeling).

Seasonal Calcification Rates and Calcite-Dependent Optical Back Scattering in the Gulf of Maine

Lisa M. Graziano, William M. Balch,
David Drapeau, Bruce Bowler
Bigelow Laboratory for Ocean Sciences,
PO Box 475, McKown Point,
West Boothbay Harbor, ME 04575
207-633-9600 lgraziano@bigelow.org

A cruise was carried out in March of 1996 to measure calcification rates and calcite-dependent optical back scattering in the Gulf of Maine. Vertical profiles at six depths were taken at a number of stations throughout the Gulf, for measurement of 14C uptake into organic and inorganic carbon over 24 hours. Additional surface samples were taken between stations for incubation. For each productivity sample taken, samples were collected for determination of particulate calcite and for enumeration of coccolithophorids and detached coccoliths. A continuous flow-through system logged surface water pH, temperature, salinity, in vivo fluorescence, and optical back scattering before and after dissolution of calcite, at all times while the ship was underway. Measurements of optical back scattering due to calcite (bb') are compared with particulate calcite values as well as cell and coccolith counts. From numbers of free coccoliths and their production rate, the turnover time of calcite particles has been estimated.

Gulf of Maine carbon budgets do not currently include estimates of calcification rates and the flux of calcite to the sediments, processes which rival organic production in terms of carbon ultimately buried in the sediments. As of this writing, we are preparing for our second cruise in late May, during which we will take profiles at 20 stations. A third cruise in the fall of 1996 will complete this work, from which we will produce a regional and seasonal map of organic and inorganic carbon fixation, estimate the turnover time of calcite parti cles, and determine the proportion of optical back scattering due to calcite in the Gulf of Maine.

(Key Words: calcification, primary productivity, backscattering)

Quantification of the Dilute Sedimantary "Soot-Phase": Implications for PAH Specification and Bioavailability

Örjan Gustafsson
R. M. Parsons Laboratory, MIT 48-320,
Department of Civil and Environmental Engineering,
Massachusetts Institute of Technology,
Cambridge, MA, 02139 omgustaf@mit.edu;
617-253-4124 617-253-7475
Department of Marine Chemistry and
Geochemistry, Woods Hole Oceanographic Institution,
Woods Hole, MA

Farnaz Haghseta, Charmaine Chan,
John MacFarlane, Philip M. Gschwend
R. M. Parsons Laboratory, MIT 48-415,
Department of Civil and Environmental Engineering,
Massachusetts Institute of Technology, Cambridge, MA

The phase-distribution of hydrophobic organic compounds (HOCs) dictates the extend to which any such chemical may participate in other transport and transformation processes. Information about this chemical speciation is thus crucial for predicting the bioavailability of many xenobiotic compounds.

Polycyclic aromatic hydrocarbons (PAHs) are a class of primarily combustion-derived contaminants, which therefore are believed to be introduced into the environment in close association with soot. There are indications in existing field data the soot-like phases may significantly affect the PAH speciation in nature. While traditional hydrophobic partition models, Pms, (Karickhoff et al., 1979; Chiou et al., 1979) predict that their distribution coefficients (Koc's) should be slightly less than the chemical's Kow, several recent investigations have reported in situ Koc's for PAH that are 1-2 orders of magnitude larger than such predictions.

In order to expand the HPM framework to include partitioning with anthropogenic soot phases, we need to quantify fsoot, the total soot carbon fraction of the solid matrix, and Ksoot, the soot-carbon normalized partition coefficient. To this end, we have developed a method that allows quantification of soot carbon, SC, in dilute and complex sedimentary matrices. Organic inorganic carbonates are removed by in situ acidification. The residual SC is then determined by CHN elemental analysis. The selectivity of the soot carbon method was confirmed in tests with matrices of known composition.

As a final test on the robustness of the soot quantification technique, we applied the method to two sets of natural sediments, both previously analyzed for PAHs. The input histories of PAHs and soot recorded in a lacustrine sediment core followed the same general trends and we this infer a coupling between the two. Our measures of fsoot and calculations of Ksoot, from studies of previously generated in situ Koc's (McGroddy et al., 1995, 1996). Intriguingly, we find that the elevated PAH kd's of two marine sediment-porewater systems are now quantitatively explainable through the extended, soot-partioning inclusive, partition model.

The importance of the soot-phase for PAHs in the environment has implications for how we perceive (and should test) in situ bioavailability and consequently also for the development of sediment quality criteria.

(Key Words: sediments, aromatic hydrocarbons (PAH), bioavailability, fossil fuel)

The Role of the Surface Ekman Layer in the *Calanus* Supply to Georges Bank

Charles G. Hannah
Oceadyne Environmental Consultants, 373 Ridgevale
Dr., Bedford, NS, B4A 3M2 Canada
902-835-6235 channah@emerald.bio.dfo.ca

Christopher E. Naimie
Dartmouth College, Hanover, NH, 03755-8000
603-646-2119 christopher.e.naimie@dartmouth.edu

John W. Loder
DFO, BIO, Dartmouth, N.S., B2Y 4A2 Canada
902-426-8968 jloder@emerald.bio.dfo.ca

Francisco E. Werner
Marine Sciences Program,UNC,
Chapel Hill, NC 27599-3300
919-962-0269 cisco@marine.unc.edu

Potential pathways for the supply of *Calanus finmarchicus* from the Gulf of Maine to Georges Bank from winter to summer have been examined using mean and tidal flow fields computed on realistic geometry using the 3-d comprehensive circulation model of Lynch et al. (CSR, 1996) and observed (climatological seasonal mean) winds and density fields. The analysis indicates that seasonal changes in the wind forcing and the depth and strength of the surface Ekman layer play an important role in the annual cycle of the supply of *Calanus finmarchicus* from the Gulf of Maine to Georges Bank. Here we examine the role of the wind-driven flows in providing both a direct pathway across the Gulf to the northern flank of Georges Bank, and a mechanism for crossing the northern flank and reaching the bank. The sensitivity of the results to unmodelled flow components is also examined.

(Key Words: Georges Bank, Gulf of Maine, seasonal circulation, Calanus, surface Ekman layer)

Sudies on the Effect of the Frontal Zone on the Northern face of Georges Bank, Gulf of Maine, on Larval Lobster and Plankton Distribution

G.C. Harding
Biological Sciences Branch,
Department of Fisheries and Oceans,
Bedford Institute of Oceanography, P.O. Box 1006,
Dartmouth, Nova Scotia B2Y 4A2, Canada;
902-426-2672 gareth.harding@maritimes.dfo.ca

K. Drinkwater
Physical and Chemical Sciences Branch,
Department of Fisheries and Oceans,
Bedford Institute of Oceanography, P.O. Box 1006,
Dartmouth, Nova Scotia B2Y 4A2, Canada

J. Prena
Am Schwibbogen 7, D-18055 Rostock, Germany

J.D. Pringle
Biological Sciences Branch,
Department of Fisheries and Oceans,
Halifax Fisheries Research Laboratory, P.O. Box 550,
Halifax, Nova Scotia B3J 2S7, Canada

A. Fraser
Biological Sciences Branch,
Department of Fisheries and Oceans,
Bedford Institute of Oceanography, P.O. Box 1006,
Dartmouth, Nova Scotia B2Y 4A2, Canada

S. Pearre, Jr.
Department of Oceanography, Dalhousie University,
Halifax, Nova Scotia B3H 4J1, Canada

R.I. Perry
Biological Sciences Branch,
Department of Fisheries and Oceans,
Pacific Biological Station, Hammond Bay Road,
Nanaimo, British Columbia V9R 5K6, Canada

W.P. Vass
Biological Sciences Branch,
Department of Fisheries and Oceans,
Bedford Institute of Oceanography, P.O. Box 1006,
Dartmouth, Nova Scotia B2Y 4A2, Canada

Geographic coverage of offshore waters in the northeastern Gulf of Maine indicates that larval lobsters are hatched and released over the offshore banks. In detailed larval studies near Georges Bank the first and second moult stages were found primarily over the bank, whereas stages III and IV lobster were collected both over and off the bank. At times Stage IV lobsters appeared more abundant off of Georges Bank than over it. The higher lipid index, triacylglycerol/sterol ratio, measured in stages III and IV collected off the Bank, on two separate years, is interpreted to indicate better growing conditions for the later planktonic stages of the lobster over deeper waters of the Gulf of Maine.

Loran C drifters, drogued at 10-m depth, were used to track larval lobsters located both over and off the northern edge of Georges Bank. Lobster larvae were sampled with a Vass-Tucker trawl at least three times over a two-day period while following three drifters off and three drifters on the Bank. The lobster stage composition and abundance did not change significantly around the three off-Bank drifters. This was not the case for the larval patches tracked over the Bank, where the first two developmental stages dominated. The more pronounced diurnal vertical migration of stages I and II lobsters in the upper 30 m probably results in their separation from the drifters due to exposure to different current shears. Stages+III and IV lobster are more surface-living throughout the day and would be expected to stay in the vicinity of a surface-drogued drifter.

Plankton transects taken across the northern tidal front over Georges Bank indicate that species inhabiting the surface waters are relatively unaffected by this hydrography and are distributed throughout the transects. This is a possible explanation as to how some lobster larvae could escape the retentive properties of the gyre over Georges Bank to complete their development and possibly settle in other locations the Gulf of Maine. Planktonic larvae of various groundfish are thought to retain their position on the Bank by not entering the surface waters.

(Key Words: Homaris americanus, frontal study, larval drift, condition index, Georges Bank)

A New Community State in the Southwestern Gulf of Maine?

Larry G. Harris
Department of Zoology, University of New Hampshire, Spaulding Life Science, Durham, NH 03824
603-862-3897 lharris@christa.unh.edu

Prior to the late 1970's, kelp beds dominated by a canopy of *Laminaria* spp. and an understory of *Chondrus crispus*, were considered the climax community in the subtidal Gulf of Maine. A sharp increase in sea urchin, *Strongylcentrotus droebachiensis*, populations created an alternate stable state community in this environment, urchin barrens. In recent years, disease and harvesting have suppressed urchin populations to levels where these barren communities are now susceptible to invasions from both native and introduced species. Ephemeral algae now occupy space in urchin barrens and provide prime substrate for recruitment of *Mytilus edulis*. These mussel beds have attracted large numbers of sea stars, *Asterias* spp. which overwhelm mussel populations. When mussel densities decline due to predation, sea stars cannibalize each other. Space that was once occupied by mussels once again becomes covered with ephemeral algae and the following year, even larger *Mytilus* beds become established. A progression of algae, mussels, sea stars and algae oscillating on a two year cycle may represent a new community state in the southwest Gulf of Maine.

The apparent instability of urchin barrens has also allowed for the successful invasion and establishment of the colonial tunicates *Botrylloides diegensis* and *Diplosoma* spp., the bryozoan *Membranipora membranacea*, and the alga *Codium fragile*. Both *Codium* and *Botrylloides* have expanded their niches; they are now common on exposed sites. Prior to 1990, they only occurred in protected habitats. *Membranipora* has also expanded its distribution; it is now able to maintain itself on a variety of algal and rock surfaces, whereas it had previously been restricted to the flat surfaces of kelp blades. *Diplosoma* spp. is the most recent invader in the subtidal environment of the southwest Gulf of Maine, it first appeared at the Isles of Shoals in 1992. By the summer of 1995, it comprised less than .01% cover of bottom space. Six weeks later, *Diplosoma* covered 60% of the substrate surface at depths ranging from 2-15 m. Reductions in native species due to sustained overharvesting may have contributed to the susceptibility of this system to invasions. The long term implications of such a shift in community structure are unknown.

(Key Words: Gulf of Maine, invasions, community structure, fishery, stability)

The Effect of Particle Surface Properties on the Transport and Fate of Trace Metals in the Water Column

Barbara H. Healy, Gordon T. Wallace
Environmental Sciences Program,
University of Massachusetts-Boston,
100 Morrissey Blvd, Boston, MA, 02125
617-287-7464 G5578BHEAL@umbsky.cc.umb.edu

In an effort to determine factors affecting differences in the affinity of suspended particles in the marine water column to adsorb trace metals, we are testing the hypothesis that particles with hydrophobic surfaces have different metal adsorption capacities than those with hydrophilic surfaces. In experiments where K_ds are calculated, it is often inherently assumed that particles in the suspended matter have similar surface properties relatively independent of the composition of the particulate phase. We have conducted experiments to separate particles in a coastal water sample according to their surface-active properties using an adsorptive bubble separation process. Coastal water samples were found to contain higher concentrations of metals in particles with surface-active, hydrophobic surfaces relative to those with non-surface-active, hydrophilic surfaces. Iron, copper and zinc were an order of magnitude higher in concentration in the particulate phase of the hydrophobic fraction relative to their respective concentrations in the particulate phase of the hydrophilic fraction. These results suggest that compositional differences, especially those affecting the surface characteristics of these particles, are important in modifying the affinities of metals for suspended

matter. Characterization of the sorption properties of these particles is being undertaken as well as determination of the environmental variables affecting differences in the relative abundances of these two types of particles.

(Key words: trace metals, particle surface properties, partition coefficients)

Transport Pathways Into and Out of the Maine Coastal Current – Numerical Modeling of the Maine Coastal Current in Spring

Monica J. Holboke
Dartmouth College, 8000 Cummings Hall,
Hanover,N.H. 03755
603-646-2685 holboke@enki.dartmouth.edu

Daniel R. Lynch
Dartmouth College, 8000 Cummings Hall,
Hanover, N.H. 03755
603-646-2308 Daniel_R_Lynch@dartmouth.edu

The Maine Coastal Current(MCC) is initiated off the eastern coast of Maine and circuits the Gulf of Maine in a counterclockwise direction transporting various nutrients, biological species, and pollution. Its role in the ecosystem of the Gulf of Maine is of significant importance not only as a transporter, but also as an interface between remote Gulf waters and local coastal waters. The Gulf waters are mainly composed of Scotian Shelf water, that is relatively fresh and cold, and Slope water, that is saline and warm. The coastal waters are dominated by local river runoff. In an attempt to understand how the MCC affects the ecosystem in the Gulf of Maine a realistic modeling capability must be achieved. The work presented demonstrates that ability by incorporating observations into forcing parameters used in a three-dimensional nonlinear time-stepping numerical model of the Gulf of Maine and specifically the MCC. Spring is chosen for its large river runoff, observed intensification of the MCC, and for dynamic atmospheric forcing. Combination of the numerical dynamic results with passive Lagrangian particle tracks makes it possible to infer pathways of various biological species, nutrients, and pollutants around the Gulf of Maine via the MCC and the origin of these contents.

(Key Words: Maine Coastal Current, coastal ocean modeling, transport pathways)

Relationship Between Postlarval Supply and Benthic Recruitment of Lobsters *(Homarus americanus)* in the Western Gulf of Maine

Lewis S. Incze, Richard A. Wahle,
Terry Ainaire, Peter Aas
Bigelow Laboratory for Ocean Sciences,
West Boothbay Harbor, ME 04575
207-633-9600 lincze@bigelow.org

James Burke
Oregon State University Corvallis, OR 97331

Marcia Bowen
Normandeau Associates, Yarmouth, ME 04096

Lobsters develop through three planktonic larval stages and a final postlarval (PL) stage which is predominantly neustonic. During seven years of study, 1989-1995, interannual variations in sea surface temperature (SST) in May and June at Boothbay Harbor led to estimated total larval development times as short as 25 d and as long as 41 d in local coastal waters. PL development times had a much smaller range, from 20 to 23 d, due to less variability of mid-summer SST and a shallower slope of the temperature-response curve over the observed range of mean temperatures, 14.5° - 17.5° C. Our most detailed sampling of postlarvae was in the Johns Bay region, at about 43° 50' N. There, postlarvae were present for a median period of 51 d from mid-July to early September, but there were large between-year differences in PL season length (range = 35-72 d) and in the timing of first appearance (Day of Year 182-206). Most postlarvae in the study area were in advanced intermolt stage, indicating that they had been advected into the region. An index of PL abundance for the season shows a nearly three-fold difference from minimum to maximum year (123 to 320 PL-days/1000 m^2/season). Young-of-the-year (YOY) benthic lobsters (carapace length ≤10 mm) are found primarily in subtidal cobble habitat, and in Johns Bay had average annual recruitment densities ranging from 0.3 to 1.5/m^2. The average density of new recruits was positively correlated with the seasonal supply of postlarvae: YOY = 5.0 * PL-days/season ($r^2 = 0.89$; SE of regression = 0.44). The relationship is improved if just late intermolt postlarvae are used. A series of experiments using standardized cobble plots showed that the observed recruitment levels of YOY lobsters did not saturate the natural cobble habitat we have been sampling. We have shown that surface transport (wind and tidal forcing) can affect recruitment levels between sites, and we hypothesize that a combination of transport and site selection by postlarvae might account for much of the 5-fold average increase observed from postlarval stage to YOY recruitment. We are now investigating the role that transport processes may play in interannual variations in postlarval abundance at the coast. A quasi-synoptic survey of lobster postlarvae from offshore stations south to Cape Ann (42° 39' N) in one year and seven years of weekly data at Seabrook, New Hampshire (42° 50' N) show that the Johns Bay PL data are typical of a large region of the western Gulf of Maine.

(Key Words: Lobster, larvae, recruitment, transport, settlement.)

Changes in the Water Quality Conditions of the Rivers of the Gulf of Maine Over the Past Century

Norbert A. Jaworski
Retired U.S. EPA, 202 Wordens Pond Road,
Wakefield, RI 02879
401-783-7483 jaworksi@uriace.uri.edu

Leo J. Hetling
Retired NYDEC, 10 Gladwish Road,
Delmar, NY 12054

As part of our study of the nutrient and mineral fluxes of the Middle-Atlantic and Northeast Coastal watersheds, we have compiled both current data (1990-1993) for 33 water quality monitoring sites. We also examined the changes in nutrient and mineral concentrations over time for 19 watershed in the middle-Atlantic and northeastern United States which are either drinking water or U.S. Geological/State monitoring sites. These data cover most of this century and come from drinking water monitoring programs (unpublished reports from municipal drinking water authorities) and from the published U.S. Geological Water Resource Data annual reports. Both rivers and reservoirs are included; generally, data reflect monthly sampling. To assess the quality of the early data, we compared them with aperiodic water quality data measured by the U.S. Geological Survey between 1905 and 1920 and by the Massachusetts State Health Agency from 1890 to 1915. We also compared the recent drinking water data with recent U.S. Geological Survey data. In general, we were surprised to have very good agreement where data sets overlapped.

In our presentation, we will compare the current nutrient and mineral fluxes of the Gulf of Maine rivers to those of the Southern New England and Mid-Atlantic Bights. Higher TOC fluxes for the Gulf of Maine rivers was an unexpected finding. For the Merrimack, Androscoggin, Penobscott, and St. Johns Rivers, historical changes will be presented, likewise for the Quabin Reservoir and Sebago Lake. Significant increases in chlorides, nitrates, sulfates, and total residue has occurred over the past century.

(Key Words: watershed, water quality, nutrients, minerals, fluxes)

The Incidence and Survival of Pathogenic Vibrious in Great Bay Estuary

Stephen H. Jones
Department of Natural Resources,
Jackson Estuarine Laboratory,
University of New Hampshire, Durham, NH, 03824
603-862-2175 shj@christa.unh.edu

Beata Summer-Brason
Department of Microbiology, Jackson Estuarine
Laboratory, University of New Hampshire,
Durham, NH, 03824 603-862-2175

Pathogenic vibrios are indigenous to temperate estuaries and have been consistently isolated from the Great Bay Estuary, New Hampshire from May to October. The incidence of two vibrios species, *Vibrio vulnificus* and *Vibrio parahaemolyticus*, was monitored at 8 sites along a salinity transectin Great Bay for 2 years. Colony hybridization with a non-radioactive fluorescein nucleic acid probe and/or traditional culture techniques were used to detect the two vibrios in field water samples. Laboratory microcosms were established for 4 successive seasons using water from 2 transect sites to determine abiotic and biological influences on the viability and survival of the two vibrios. The sites were characterized by high and low extremes of vibrio levels, nutrients, and salinity. Rhodamine staining of inoculated vibrios permitted direct counts to be compared to culturable and total counts.

The incidence of vibrios was found to be corre-

lated to many environmental parameters, including temperature, fecal contaminant and nutrient levels, primary productivity, and salinity. Regression analysis showed certain parameters helped predict the incidence of the vibrios in the estuary. Growth and survival in sterile and non-sterile microcosms were influenced by predation, temperature and competition. The gene probe for *V. vulnificus* gave more consistent results and generally higher levels were detected. The study indicates that a combination of chemical and biological parameters, and not just temperature and salinity, are important factors that determine the survival of the vibrios in estuaries.

(Key Words: bacterial pathogens, *Vibrio vulnificus, Vibrio parahaemolyticus,* survival, estuarine environment)

Abundance and Distribution of Phaeocystis SP. in the Gulf of Maine, U.S.A.: Spring Bloom Dynamics and Bloom Initiation

Maureen D. Keller
Bigelow Laboratory for Ocean Sciences,
West Boothbay Harbor ME 04575
207-633-9600 mkeller@bigelow.org

Elin M. Haugen
NMFS/NOAA Laboratory, Beaufort NC 28516
919-728-8792 ehaugen@hatteras.bea.nmfs.gov

The springtime appearance of the phytoplankter, Phaeocystis, has been commonly reported in the Gulf of Maine since the 1920's, but only as a brief minor component of the flora dominated by diatoms. We have collected information on the abundance and distribution of Phaeocystis over a three year period in offshore and nearshore waters of the Gulf. This species appears to be more abundant and persistent than historical records indicate. In each of three years, we found large, subsurface populations of Phaeocystis in the area of Stellwagen Basin, located offshore of Massachusetts Bay, a large, coastal bay located in the western Gulf of Maine. Inshore populations appear to be seeded from these offshore populations, which apparently originate at depth in the Basin. Light availability may play a key role in the development of these blooms. Nutrients (nitrogen or phosphorus) were not limiting and did not appear to play a critical role in either the initiation or cessation of the bloom. The main Phaeocystis bloom appears to precede or co-occur with the spring diatom bloom in these waters, rather than follow it, as it does in other temperate areas. Its ability to utilize low light levels and to grow vigorously at low temperatures (< 4oC) may confer a competitive advantage in the Gulf of Maine in early spring. Phaeocystis sp. have a complex life cycle, consisting of two known single cell phases, flagellated and non-motile, and a distinctive colonial form. All three phases have been observed in the Gulf of Maine, and the single cell phase dominates. The colonial form of this alga forms large, noxious aggregates in many areas of the oceans and is known to respond to eutrophication. Phaeocystis is also known to produce significant amounts of the atmospherically-important sulfur gas, dimethyl sulfide (DMS). Very high concentrations (>500 nM) of DMSP, the precursor of DMS in algae, have been measured coincident with Phaeocystis populations in the Gulf of Maine. For these reasons, its presence and occasional dominance warrant further investigation.

(Key Words: phytoplankton, Phaeocystis, spring bloom, bloom dynamics, light)

Physiography and the origin of Seafloor Sedimentary Habitats: Northern Massachusetts to Canada, Shoreline to 100 M Isobath

Joseph T. Kelley, Stephen M. Dickson
Maine Geological Survey, 22 State House Station,
Augusta, ME 04333-0022
207-581-2162 jtkelley@maine.maine.edu

Walter A. Barnhardt
Daniel F. Belknap
University of Maine,
Department of Geological Sciences, Orono, ME
207-581-2155 walterb@raven.spatial.maine.edu

Synthesis of bathymetric data (10 m contour interval), 1303 bottom samples, 3358 km of side scan sonar, and 5011 km of seismic reflection profiles allow definition of regional seafloor physiography and habitat origin in the northwestern 10,300 km^2 of the Gulf of Maine. The physiographic zones defined experience different oceanographic conditions (i.e. temperature, salinity, etc.) similar to the different environmental conditions of terrestrial, biophysical regions. As a result they ought to possess differing faunal assemblages regardless of sediment texture.

For the past 10ka, the seafloor has evolved under conditions of rising sea level, which has resulted in the redistribution and general seaward transfer of sediment. Seaward of 60 m, mud blankets 79% of the surface of Outer Basins (21% of study area), regions of continuous Holocene sedimentation. Landward of 60 m, Rocky Zones (RZ, 45% of study area), where sea-level changes have stripped off glacigenic sediment, are dominated by rock (71%) and gravel (10%). Shelf Valleys (SV, 7% of study area) are deep, narrow, seaward descending troughs cut through RZ's and may be conduits for onshore-offshore movement of materials. Although glacial deposits are largely eroded from these 33 bedrock-framed channels, Holocene mud covers 63% of the seafloor. Nearshore Basins (17% of the study area) lie in < 30 m of water and are landward, filled extensions of SV's. They accumulate mud from coastal bluff erosion, and are muddy (77% mud) and smooth except where giant, gas-escape pockmarks have formed. Nearshore Ramps (4% of the study area) dip gently seaward from sandy beaches in southern ME and NH. They are wedge-shaped deposits of sand (65% surficial sand) that are transgressing landward with rising sea level. Hard-Bottom Plains (6% of the study area) are flat, gravelly (83% gravel) regions near eroding till deposits in southern Maine and near Grand Manan Island.

(Key Words: physiography, seafloor habitats, side-scan sonar, inner continental shelf).

Ecology of Nearshore Fish Communities in Maine

Mark Lazzari, Sally Sherman, Clarisse Simard-Brown, Bruce Joule, Richard Langton
Maine Department of Marine Resources,
P.O. Box 8, W. Boothbay Harbor, ME 04575
207-633-9569 mrmlazz@state.me.us

We examined habitat use of an intertidal mill pond and beach on the central coast of Maine by young-of-the-year commercially and ecologically important nearshore fishes. Fyke net and beach seine samples were collected biweekly from April, 1990 - December, 1994. The fyke net was set in the inlet channel of the mill pond at low tide and allowed to fish for three hours of the flood tide while a single seine sample was collected on the beach at low tide, and a second sample collected three hours into the flood tide.

Twenty-seven species of fishes were caught by fyke net and seine during the 5 year study of the intertidal mill pond and sandy beach at Kennebec Point, Maine. There were considerable differences in the species composition of the fyke and seine catches such that neither alone provided an adequate description of the sampled community. Approximately bimonthly sampling demonstrated a clear seasonal cycle in abundance and species composition. A few species were resident in the mill pond and on the beach all year round; the majority were only present from spring through autumn. Increases in both the numbers and species were caused mainly by the recruitment of young-of-the-year individuals whose numbers subsequently declined gradually, probably due to a combination of predation and emigration. There were marked similarities in both species composition and abundance between years. Annual cycles in species richness and abundance closely paralleled those of temperature. It is suggested that the cycles result mainly from recruitment and mortality rather than from immigration and emigration in response to physical factors.

(Key Words: habitat use, nearshore fishes, Kennebec Point)

Benthic Fluxes of Polycyclic Aromatic Hydrocarbons Out of Boston Harbor Sediments

Gongmin Lei, Robert F. Chen
Environmental Sciences Program,
University of Massachusetts Boston,
100 Morrissey Blvd., Boston, MA 02125
617-287-7448 g3056glei@umbsky.cc.umb.edu

The benthic fluxes of nine polycyclic aromatic hydrocarbons (PAH) out of Boston Harbor sediments have been estimated by using a mathematical model which is:

$$F = -\varphi \bullet (D_s + D_b) \bullet (\partial C / \partial Z) + \varphi \bullet \alpha \bullet \int (C_{pw} - C_b) \cdot dZ$$

where

F: PAH flux due to molecular diffusion, bioturbation and bioirrigation ($ng/cm^2\ y$)

φ: Porosity

D_s: Molecular diffusion (cm^2/s)
D_b: Bioturbation coefficient (cm^2/s)
α: Irrigation coefficient (1/s)
C_{pw}: PAH concentration in porewater (ng/l)
C_b: PAH concentration in bottom water (ng/l)
Z: Depth of sediments (cm)

Surface sediments and bottom water were taken at five stations of Boston Harbor. Porewater was obtained by centrifugation. Porewater and bottom water were filtered, extracted with DCM, cleaned up with silica gel column. Nine individual PAH in porewater and bottom water were quantified by GC-FID and GC-MS. Solid sediments were soxhlet extracted with DCM and methanol, and analyzed as above.

The measured PAH concentrations in porewater and sediments were used to calculate apparent organic carbon normalized partition coefficients (K_{oc}') for each PAH. It was found that most of K_{oc}'s are much larger than literature values, possibly suggesting incomplete partitioning of solid phase PAH into porewater. Available for equilibrium partitioning (AEP) fractions of PAH were calculated, and maximum AEP was only 50% for anthracene at Font Point Channel in Boston Harbor. The AEP of other PAH at all stations were less than 50%. D_s was corrected for porosity and tortuosity. D_b and α were cited from literature. It has been shown that both bioturbation and molecular diffusion play much larger roles in benthic fluxes of PAH out of sediments than irrigation. Colloids could enhance the fluxes of high molecular weight (MW) PAH such as benzo(a)pyrene more than low MW PAH such as phenanthrene. PAH in solid phase used to estimate the fluxes of PAH out of sediments could largely overestimate the PAH fluxes, because some of PAH in solid phase are not available for equilibrium partitioning. The results also showed that the benthic fluxes of PAH to water column of Boston Harbor could be significant compared with other fluxes of PAH such as river and atmosphere.

(Key Words: Polycyclic Aromatic Hydrocarbons, Benthic Flux, Molecular Diffusion, Bioturbation, Irrigation, Boston Harbor, Sediments)

Morphological Comparisons of Larval Herring *(Clupea harengus)* Otoliths Collected in Three Distinct Spawning Areas in the Gulf of Maine.

David A. Libby
Maine Department of Marine Resources,
Boothbay Harbor Laboratory,
West Boothbay Harbor, ME 04575
207-633-9532 mrdlibb@state.me.us

Kevin D. Friedland
National Marine Fisheries Service,
166 Water Street, Woods Hole, MA 02543
508-548-5123 kfriedla@whsun1.wh.whoi.edu

The shape of sagittal otoliths from larval herring collected from three distinct spawning areas within the Gulf of Maine was compared. Otoliths from larvae of similar size and growth rate were compared. Thirty-two pairs of Fourier descriptors (amplitude and phase angle) as well as morphological measurements of area, perimeter and major axis were collected with the use of a computer based image analysis system. Two separate sets of Fourier descriptors were derived using 1) the otolithÕs centroid as center (CT) and 2) using the otolithÕs nucleus (NU) as center. Discrimination variables were selected using stepwise procedures. Analyses were performed for 1) CT and NU extractions, 2) left and right otoliths between the three areas and 3) between left and right otoliths in each area and for all areas combined. The highest classification successes occurred using right otoliths and treating the nucleus as the center. Moderate classification success was achieved for a three group model discriminating spawning areas. Simplified models comparing spawning area pairs had higher classification rates.

(Key Words: Gulf of Maine, larval herring, otolith shape, Fourier analysis).

Spring Pulse and Annual Nutrient Input by the Kennebec River to the Western Gulf of Maine Coastal Zone

Theodore Loder III, Marie Evans, Robert Boudrow, Cathy Coniaris, Heather Benway, Caroline Martorano, Andrew Schoudel
Estuarine/Coastal Chemistry Laboratory,
Institute for the Study of Earth, Oceans, and Space,
University of New Hampshire, Durham, NH 03824
603-862-3151 t.loder@unh.edu

This project was designed to determine the input of nitrogen, phosphorus, and silica to the western Gulf of Maine coastal zone during the biologically critical spring period when nearly half of the annual river input occurs during a 2 month period. This high runoff occurs because of annual spring snow melt which peaks on average around the last week of April. This runoff sets up the western Gulf of Maine coastal plume which can be tracked from its input into Massachusetts Bays and out into the Gulf of Maine east of Cape Cod. Nutrient concentrations and ratios in the river water are different than those in coastal seawater and may affect spring bloom and subsequent red tide dynamics as water moves down the coast.

During the spring of 1994 (March 14 to May 25), 52 water samples were collected every one to three days in the Kennebec River at a location 4 km upriver from the town of Bath, ME just above the start of estuarine mixing. These samples were analyzed for the following components: dissolved inorganic nutrients including: nitrate, nitrite, ammonium, phosphate, and silicate; dissolved organic nitrogen and phosphorus; and particulate carbon, nitrogen, and phosphorus. The concentrations of all nutrients after the spring runoff period were about one half of their concentration prior to this period and continued to decrease during the summer months. However, concentrations of particulate nitrogen, carbon and phosphorus increased during high flow periods.

Using these and other unpublished data, including samples collected early in the year and during the late summer months, we were able to estimate the river nutrient concentrations throughout the year. Using these data and river flow rates, we were then able to calculate nutrient ratios and mass inputs of the different forms of these nutrients into the coastal zone during the critical spring period and estimate annual inputs into the western Gulf of Maine.

(Key Words: Kennebec River, nutrients, annual input, spring runoff, coastal plume)

Georges Bank Review – Canada & Nova Scotia

Ron Loucks
R. H. Loucks Oceanology Ltd.,
Stewardship of Water Resources, Halifax, Canada
902-443-1113 rloucks@atcon.com

This poster outlines first the background for the 1988 moratorium on petroleum exploration and drilling on the Canadian sector of Georges Bank and the legislated requirement for a review before the year 2000. Then the review process, which has begun, is outlined. It includes addressing relevant knowledge gaps, information sessions, workshops and public hearings.

Zooplankton Faunal Zones and Their Relationship to Hydrography and Ichthyoplankton Production in the Georges Bank Region

George R. Bolz, **R. Gregory Lough**
NMFS/NEFSC, 166 Water St., Woods Hole, MA 02543
508-495-2290 glough@whsun1.wh.whoi.edu

The distribution and abundance of zooplankton have been examined for 15 ICNAF Larval Herring Surveys covering the Georges Bank©Nantucket Shoals region during the autumn and winter seasons, 1973-77. Numerical classification techniques delineated three distinct and dynamic faunal groupings: 1) a zone located along the southern flank of Nantucket Shoals and Georges Bank, composed of oceanic and slope water species and characterized by high diversity and low abundance; 2) a shelf faunal zone centered on the shoaler, central portions of Georges Bank and Nantucket Shoals, dominated by species endemic to the area and exhibiting high abundance and moderate diversity; and 3) a zone found along the northern edge of Georges Bank and extending into the Gulf of Maine, inhabited by many of the same taxa found on the shelf but in lower abundances. The clustering of zooplankton species conformed to the circulation of the prevailing water masses and was able to delimit gross seasonal and annual fluctuations. Zooplankton distributional anomalies, such as geographical displacement following prolonged periods of wind stress or broadscale intrusions of Slope Water onto the southern flank of Georges Bank, were clearly highlighted. Despite year-to-year fluctuations zooplankton abundance on Georges Bank and Nantucket Shoals appeared to be more stable than that noted for larval fish. Comparison with more recent years was examined to determine if any long-term trends were discernible.

Decision Support System to Facilitate Protection of Habitat for Priority Species in Passamaquoddy Bay

Gregory F. Gillis, **Cathy A. MacKenzie**
Washburn & Gillis Associates Ltd., 25 Waggoners Lane, Fredericton, New Brunswick, Canada E3B 2L2

ICOIN Industries Inc. is developing a knowledge-based decision support system for three New Brunswick government clients:

- a Spill Response Application in the Passamaquoddy Bay for the New Brunswick Emergency Measures Organization;
- a Sustainable Development Application in the Nepisiguit River watershed for the New Brunswick Department of Fisheries and Aquaculture; and,
- a Habitat Protection Application in the Passamaquoddy Bay for the New Brunswick Department of the Environment.

The Inland Waters Coastal and Oceans Information Network Node being developed for each client is comprised of an information management system; metadata directory of data sets in the study area; knowledge based software linking application data requirements and regulatory constraints to available data sets; and a Caris geographic information system for modeling and displaying application output.

The Habitat Protection Application is being developed in consideration of the Gulf of Maine Council's Priority Habitat Initiative and will incorporate species specific models in determination of habitat availability and susceptibility to anthropogenic effects.

(Key Words: Gulf of Maine Council, habitat protection, Passamaquoddy Bay, knowledge-based system, ICOIN)

An Analysis of Nutrients Affecting *Alexandrium Tamarense* Blooms in the Gulf of Maine

Caroline Martorano, Theodore Loder III
Estuarine/Coastal Chemistry Laboratory,
Institute for the Study of Earth,
Oceans and Space, University of New Hampshire,
Durham, NH 03824
603-862-1542 cdm2@christa.unh.edu

Toxic and non-toxic blooms of dinoflagellates, diatoms, and other groups of photosynthetic microalgae are termed "red tides" when the tiny pigmented plants grow in such abundance that they change the color of the seawater to red, brown, green or even yellow. Many studies reveal that the number of algal blooms along the world's coastlines have escalated over the last several decades. Such events have been correlated to the increased levels of nutrient runoff, primarily from increased sewage and fertilizer use. Airborne nitrous oxides (from automotive and smokestack emissions) are also a source of excess nitrogen to the coasts.

The Gulf of Maine has had numerous outbreaks of toxic dinoflagellate blooms of *Alexandrium tamarense* since 1972. In 1993, a regional group of scientists began a three year study of this natural phenomenon. The goal was to analyze and model the physical, biological and chemical dynamics of *Alexandrium tamarense* blooms associated with the Western Gulf of Maine coastal current. Five cruises were conducted in 1993 and six in 1994. Sampling station locations were arranged in 8 transects, from just west of Penobscot Bay to Massachusetts Bay. Sampling was conducted bi-weekly from April to June. Nearly 4,000 samples were analyzed for dissolved inorganic nutrients (phosphate, silicate, nitrate, nitrite and ammonium) at the University of New Hampshire. *Alexandrium tamarense* concentrations were analyzed at Woods Hole Oceanographic Institution.

Preliminary analyses of the data indicate some of the following trends. Due to consistent down-welling favorable winds in the 1993 field season, the plume was essentially squeezed up against the coast. As a result, PSP toxicity levels were dangerously high in Massachusetts Bays, and extended further into Cape Cod Bay then ever before. During the early spring runoff period, nutrient concentrations and ratios exhibited differences inside and outside the coastal plume.

For example, nutrient data from Cruise 2 (April 10-13) revealed that concentrations of ammonium and silicate were higher in the plume surface waters than in surface waters outside the plume. In contrast, concentrations of phosphate and nitrate were found to be lower in the surface water plume than outside of it. In addition, data collected from Cruise 3 (April 26-28) indicated that all nutrient concentrations were higher in the plume surface waters than the surrounding surface waters. However, these differences decreased in late spring and early summer as surface waters became uniformly depleted in nutrients.

(Key Words: coastal current, Alexandrium tamarense, nutrient, ratios, Gulf of Maine).

Organic Chemical Contaminants in Gulf of Maine Plankton and a Biomarker of Their Circulation in the Zooplanktivorous Right Whale

Michael J. Moore
Woods Hole Oceanographic Institution,
Woods Hole, MA 02543
508-289-3228 mmoore@whoi.edu

Carolyn Miller
Woods Hole Oceanographic Institution,
Woods Hole, MA 02543

Anne Weisbrod, Damian Shea
North Carolina State University, Raleigh, NC

John J. Stegeman
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

To better understand the linkage between content of chemical residues and trophic transfer, concentrations of polychlorinated biphenyls (PCBs), organochlorine pesticides (OCPs), and polycyclic aromatic hydrocarbons (PAHs) were measured in dissolved and particulate water fractions and two plankton size fractions from the Gulf of Maine and other sites. There appears to be a possible cline of decreasing contamination from the Bay of Fundy, to Cape Cod Bay to Georges Bank. These data, along with prior data, are being analyzed to establish estimates of chemical transfer and exposure in different trophic levels. Within one zooplanktivore, the northern right whale, the induction of cytochrome P4501A, a biomarker of exposure to aromatic hydrocarbon receptor agonists, such as coplanar PAHs and PCBs, was detected. Immunohistochemical detection of cytochrome P4501A induction in endothelial cells of epidermal/ dermal biopsies of right whales feeding where the plankton samples were taken in the Bay of Fundy showed persistent age-related induction. Thus, while these animals do not have high levels of organochlorine compounds in their tissues (Woodley et al 1992), they may have a continuous systemic exposure as these compounds are consumed and stored or mobilized and excreted. The toxicological significance of these observations along with the significance of the plankton chemical residues reported is unclear, but should be investigated given the failure of this endangered population to grow. These observations may also be relevant to the population dynamics of other members of the plankton-based food web.

(Key Words: Plankton, organic contaminants, right whales, cytochrome P4501A, biomarkers)

Trends in Tumor, and Hydropic Vacuolation Prevalence and Organic Contaminants in Winter Flounder from Massachusetts, USA - 1987 to 1995.

Michael J. Moore
Woods Hole Oceanographic Institution, Woods Hole, MA 02543
508-289-3228 mmoore@whoi.edu

Damian Shea
North Carolina State University, Raleigh, NC

Carole Peven and Robert Hillman
Battelle Ocean Sciences, Duxbury, MA

John Brown,
Arthur D. Little Inc., Cambridge MA 02140);

John J. Stegeman
Woods Hole Oceanographic Institution, Woods Hole, MA 02543

Liver lesions including neoplasia and hydropic vacuolation have been described in winter flounder (*Pleuronectes americanus*) from sites in Boston Harbor, and were highly prevalent near the Deer Island sewage outfall. A marked decline in prevalence of neoplasia was seen over the period 1987 to 1993 in fish from

near the Deer Island outfall. This decline in disease in Deer Island fish correlated with and probably resulted from reported reduced chemical input over that time. The lack of tumors has persisted to the present. Stable isotope ratios suggest that Deer Island winter flounder, in contrast to fish from elsewhere, fed significantly on sewage sludge derived organic matter prior to the cessation of sludge dumping in 1992 and that their alongshore movement is slight. Between 1991 and 1995 hydropic vacuolation remained much more prevalent in flounder taken near Deer Island and another sewage outfall than at sites distant (< 45 miles) from the outfalls. Hydropic vacuolation prevalence correlated closely with content of chlorinated hydrocarbon residues in the liver and skeletal muscle. This suggests that between 1991 and 1995 there was a persistent chemical-associated difference in fish from the planned and current outfall sites, and that monitoring of winter flounder will provide necessary assessment of altered chemical carcinogenesis risk during and after the switch to the offshore outfall planned for 1998.

(Key Words: flounder, tumors, vacuolation, Boston Harbor, biomarkers).

Atmospheric Nitrogen Deposition to the Gulf of Maine

Byard W. Mosher
CSRC, University of New Hampshire, Morse Hall,
39 College Rd., Durham, NH, 03824
603-862-4520 byard@kaos.sr.unh.edu

Robert W. Talbot, Carolyn E. Jordan
CSRC, University of New Hampshire, Morse Hall,
39 College Rd., Durham, NH 03824 603-862-1792
rwt@christa.unh.edu cjordan@kaos.sr.unh.edu

The Gulf of Maine and adjacent waters are an extremely important natural resource both ecologically and economically. This region also lies downwind of heavily industrialized and densely populated regions of the US, and thus the atmosphere represents a potentially important input pathway for both pollutants and nutrients to the Gulf. A fundamental understanding of the physical, biological, and geochemical processes operating in this coastal ecosystem is essential if we are to assess the impact of anthropogenic activities. A three year study was recently initiated as part of the Regional Marine Research Program to assess the direct atmospheric inputs of nitrogen to this region. Daily ambient concentrations of gas phase nitric acid and particulate nitrate and ammonia are measured at the New castle, NH sampling site. In addition, nitrate and ammonium levels are determined in event precipitation samples collected at this site allowing us to assess wet deposition inputs of nutrients to the Gulf.Models incorporating ambient meteorological data, nitrogen species particle size distribution, and ambient gas phase and particulate concentrations are used to calculated dry deposition fluxes.

Nitrate is found predominantly on large particles and exhibits a particle size distribution very similar to that observed for sea salt at our coastal site. This suggest that gas phase nitric acid may be reacting with alkaline sea salt aerosols in the marine boundary layer as polluted air masses move off the coast. While ammonium is largely found on small particles, the large particle ammonium dry deposition flux is still important. Episodic aerosol dry deposition events, driven by elevated nitrate and ammonium concentrations in the atmosphere, appear to be extremely important for nitrate and ammonium input. These major events of nitrate and ammonium dry deposition are not well correlated temporally, suggesting different regional sources for these two species. Similarly, one to two day episodic events have a major impact on the gas phase dry deposition flux of nitric acid to the Gulf. During periods of high ambient gas phase nitric acid concentrations, wind-field analysis indicates air masses typically have an east coast origin, passing over major metropolitan areas along the east coast, prior to arriving in the Gulf. During the 1994 sampling season wet and dry deposition inputs were approximately equivalent, depositing a total of 0.069 Tg N/yr in the Gulf of Maine. We have also observed that fog very effectively scavenges gas phase nitric acid from the atmosphere and deposition of fog borne nitrogen species to the Gulf may be a very important process in the cycling of nitrogen in the region. We estimate that N inputs to the Gulf of Maine via fog may be roughly 0.11 Tg N/yr.

Total annual atmospheric inputs are estimated to be roughly 0.18 Tg N/yr with approximately two thirds in the form of nitrate and one third deposited as ammonium. While atmospheric inputs of nitrogen to the Gulf are larger in magnitude than riverine inputs, deep flow through the Northeast Channel appears to be the dominant input mechanism for nitrogen to the Gulf of Maine.

Effects of Season and Species on Physiological conditions and Containment Burdens of Mussels (*Mytilus edulis* L. and *Mytilus trossulus* G.) in the Bay of Fundy: Implications for the Gulfwatch Program

Laura C. Mucklow
CanTox Inc., 5475 Spring Garden Rd.,
Suite 603, Halifax, N.S. B3J 3T2, Canada
902-429-0278 cantoxns@ra.isisnet.com

Gulfwatch is a coastal biomonitoring program carried out by the monitoring committee of the Gulf of Maine Council on the Marine Environment, involving the collection and chemical analysis of mussels as an alternative to sea water and sediment analysis. In conjunction with this program, a detailed study of contaminant burdens in mussels was carried out between September, 1994 and August, 1995 to determine the effects of season and species. Two species of mussels, *Mytilus edulis* and *Mytilus trossulus*, were collected monthly for one year from Digby, Nova Scotia, Annapolis Basin, Bay of Fundy. Condition index (CI) and gonad index (GI) determinations were conducted monthly for individual mussels, and composite mussel tissue samples were analyzed at four times during the year for metals (copper, nickel, cadmium, iron, aluminum, silver, lead, chromium, zinc and mercury) and organic chemicals (PAHs, PCBs and pesticides).

Seasonal profiles for CI and GI were influenced by seasonal temperatures, food availability and reproductive condition. Four different seasonal patterns were observed for metal burdens in *M. edulis*, while *M. trossulus* displayed six distinct seasonal patterns for metals. A consistent seasonal pattern was observed for all organic chemicals. No significant correlations between contaminant concentrations or burdens and CI, GI or lipid content were identified. Species differences were observed in terms of tissue weights, CI, GI, spawning times, chemical concentrations and seasonal patterns of accumulation of certain metals.

This study has shown that accurate species identification of the mussels used in the Gulfwatch program, as well as determination of suitable seasons for their collection and analysis, are necessary to avoid misinterpretation of data from this program.

(Key Words: Bay of Fundy, seasonal contaminant levels, mussel watch, species differences, condition).

Seasonal Variation in the Gulf of Maine Residual Circulation – Basin Scale Prognostic Numerical Model Results

Christopher E. Naimie, Daniel R. Lynch
Dartmouth College, 8000 Hinman, Hanover, NH 03755
603-646-2119 christopher.e.naimie@dartmouth.edu

The seasonal variation in the 3-D residual circulation for the Gulf of Maine is studied by numerically computing the circulation for six bimonthly periods (January-February, March-April, May-June, July-August, September-October, and November-December). The computations are performed using a prognostic (i.e. including tidal-time advection of the density field), free surface, nonlinear, finite element model [Lynch et. al. 1996] on realistic basin scale topography. The simulations include forcing from the dominant M_2 tide, baroclinic pressure gradients, wind stress, up-stream boundary conditions, and advanced turbulence closure.

Favorable agreement between the modeled and observed seasonal circulation supports the use of these circulation fields in studies exploring the linkage between seasonally dependent biological observations and the physical circulation for the Gulf of Maine region. The 3-D bimonthly solutions also provide an initial seasonal estimate of the physical circulation, from which studies centered on processes not modeled herein can be conducted; such as storm events, other tidal constituents, etc.

(Key Words: Gulf of Maine, seasonal circulation, numerical modeling)

Possible Transmission of Bacterial Diseases from Cultured Atlantic Salmon and Wild Fish Residing Around Sea Cages

Gilles Olivier
Fisheries and Oceans Canada,
Halifax Fisheries Research Laboratory, P.O. Box 550,
Halifax, NS B3J 2S7 Canada
902-426-7588 g_olivier@bionet.bio.dfo.ca

Anne Bacro
Ecole Nationale Superieure Agronomique de Rennes

John O'Halloran
New Brunswick Dept. of Fisheries and Aquaculture

A total of 242 fish comprising 15 species were caught around Atlantic salmon sea cages located in the Bay of Fundy during the summer months of 1991. All animals were sampled for the presence of the recognized fish pathogens, *Aeromonas salmonicida*, *Vibrio anguillarum*, *Vibrio salmonicida* and *Renibacterium salmoninarum*. No recognized fish pathogen was identified in any of these fish but 17% of the animals contained pure cultures of bacteria that could not be accurately identified. During this study, two populations of wild fish were characterized. One was transient around the various sites while the other seemed to be closely associated with a specific site. This preliminary study has provided valuable information on the methodologies required to undertake future studies on the possible transmission of diseases between wild fish and cultured fish and vice versa.

(Key Words: disease, salmonid, marine fish, transmission bacterial diseases)

Water and Sediment Temperature Variability Within the Coastal Zone of Southwest New Brunswick, Canada

Fred H. Page, Shawn Robinson, Richard Peterson
Fisheries and Oceans Canada, Biological Station,
St. Andrews, New Brunswick, Canada, EOG 2X0
506-529-8854 page@sta.dfo.ca

Temperature has long been considered a potentially important factor influencing the distribution and growth of marine organisms. The high tidal range extensive intertidal areas characteristic of the coastal zone of southwestern New Brunswick results in relatively large spatial gradients in temperatures with sub-zero water temperatures sometimes occurring in winter. In recent years interest in temperatures has increased due to its importance to the local salmon cage culture industry and the emerging shellfish enhancement and culture industries. Canada's oldest marine biological station was established in the area in St. Andrews, at the turn of the century and temperatures have been measured in the local area ever since. Although the intensity of the spatial coverage has fluctuated over the decades as research programs and socio-economic issues have come and gone, surface temperatures have been measured at least daily at the Biological Station Wharf and hydrographic profiles have been taken every month at an estuarine and offshore location throughout much of this time period, particularly since the early 1920's. Since 1989 temperature-depth profiles have been taken monthly at 25 locations within the region. Sediment temperatures on local clam flats and water temperatures at local fish farms have been measured every half hour since 1995. These data are presently being collated and analyzed in association with biological data to help assess the importance of temperature to issues such as cultured fish and shellfish production, to help identify the local circulation patterns and to begin assessing the possibility of local temperature prediction. The presentation describes some of these measurement programs and briefly outlines some of the patterns in water and sediment temperatures identified to date.

(Key Words: temperature, variation, time trends, water, sediment)

Cyclonic Circulation of the Eastern Gulf of Maine

Neal R Pettigrew
Department of Oceanography,
University of Maine, Orono, ME 04469
207-581-4384 nealp@maine.maine.edu

Robert D Hetland, John P Wallinga
Department of Oceanography, University of Maine,
Orono, ME 04469 207-581-4393

An ongoing hydrographic/drifter study, started in April, 1994 suggests a new view of the spring and summer surface circulation in the eastern Gulf of Maine. Five satellite-tracked drifters were released in the eastern gulf during the spring of 1994, 1995, and 1996. The drifter trajectories show an overall cyclonic circulation pattern in the eastern Gulf of Maine that often includes cyclonic recirculation around the Jordan and Georges Basins with opposing currents occurring in the region of Truxton Swell.

Hydrographic surveys of the region reveal density distributions that are consistent with the double-gyre patterns revealed in the drifter data. In particular the slope-water topography generally appears as a pair of "domes" over the Jordan and Georges Basins. Geostrophic calculations and direct current measurements support the notion that the cyclonic circulation pattern penetrates into the slope water. These results imply that the slope water flow is directed roughly parallel to the Truxton Swell rather than perpendicular to it, as is commonly assumed, and that the slope-water transport into Jordan Basin is either very episodic or occurs farther to the east.

AVHRR images of the Gulf are generally consistent with the circulation scheme deduced from hydrography and drifters. These results challenge the prevailing view of both the deep and shallow circulation in the eastern Gulf of Maine.

(Key Words: Circulation, Eastern Gulf of Maine, Jordan Basin Gyre, Georges Basin Gyre)

Geochemical Mass Balance Model for Lead in the Gulf of Maine

Steven M. Pike, M. A. Charette, S.B. Moran
Graduate School of Oceanography,
University of Rhode Island, Narragansett, RI 02882
401-874-6259 spike@gsosun1.gso.uri.edu

C.H. Pilskaln
Department of Oceanography, University of Maine,
Orono, ME 04469 pilskaln@maine.maine.edu

Quantification of the removal fluxes of particle-reactive contaminant trace metals is important to the development of a geochemical model for the Gulf of Maine. The goal of this work is to construct a geochemical budget for a suite of reactive contaminant metals. To date, work has focused on the removal of Pb via particle scavenging in the central Gulf of Maine. Sediment traps deployed in Jordan and Wilkinson Basins have been used to collect sinking particles on a bi-weekly basis since March, 1995. In addition, measurements of the removal flux of the naturally occurring radionuclide ^{234}Th ($t_{1/2}$=24.1 d) are being combined with Pb/^{234}Th ratios on large, rapidly settling particles (> 53 μm) collected using in situ pumps. The ^{234}Th-derived removal of particulate Pb provides an independent constraint on the removal of Pb quantified using sediment traps. Analysis of 2M HNO_3 leachable particulate Pb on the sediment trap material and particulate matter collected using pumps is currently in progress. A mass balance model for Pb, which includes input from the atmosphere and rivers, removal from the water column via particle scavenging, and sediment deposition, will be presented.

(Key Words: trace metals, lead, mass balance model, Gulf of Maine, removal flux)

An International Mercury Network: Linkages for the Gulf of Maine Ecosystem

Wilfred Pilgrim
Mercury Coordinator for the Ecological Monitoring and Assessment Network, New Brunswick
Department of the Environment, PO Box 6000, Fredericton, New Brunswick E3B 5H1, Canada
506-453-3624 wilfp@gov.nb.ca

Mercury is a priority pollutant and many countries are developing protocols for its control. An evaluation of trends from independent efforts can be hampered by the use of differing sampling and analysis protocols. To understand the significance of atmospheric inputs, linkages with extensive North American and global monitoring and research networks are essential. To better understand the priority stressors that are affecting ecosystems on a local, regional or global scale, the independent monitoring activities need to be brought together. A number of individuals and organizations have called for a more encompassing larger scale (world-wide) atmospheric mercury sampling network. This poster will describe the consolidated efforts that have been made to start a large scale network and the benefits of being a partner in such a network.

Particulate Flux Dynamics in Jordan and Wilkinson Basins: Seasonal POC Export and Particle Resuspension

Cynthia H. Pilskaln, Wayde Arnold, Charlotte Lehmann
Department of Oceanography,
University of Maine, Orono, ME 04469
207-581-4363 pilskaln@maine.maine.edu

Leslie E. Watling
Darling Marine Center,
University of Maine, Walpole, ME 04573
207-563-3146 watling@maine.maine.edu

In an effort to address the seasonal variation in the magnitude and composition of particulate organic matter (POM) export and recycling occurring within the offshore regions of the Gulf of Maine, we have deployed time-series sediment trap moorings in two of the deep, offshore basins. Results form the first six month deployment (March-September 1995) document a strong seasonal signal in particulate nutrient export (e.g., POC, PON, and biogenic silica) measured at 150m and 250m in each basin, with peak fluxes occurring in the spring following the offshore, spring phytoplankton bloom, and secondary flux peaks occurring in the summer and early fall. Total mass particulate fluxes were 2-3-fold larger in Jordan vs. Wilkinson Basin, with spring (March-April) POC fluxes averaging 165 mg m-2day-1 in Jordan Basin as compared with 40 mgCm-2day-1 in Wilkinson Basin. These data coupled with the higher spring primary production rates and substantially lower microzooplankton grazing rates measured by Sieracki and Keller (pers. comm.) in Jordan vs. Wilkinson Basin, provide preliminary support for the hypothesis that Jordan Basin is a region of POM export whereas POM recycling processes may dominate the Wilkinson Basin water column.

Transmissometer profiles have revealed the existence of a prominent bottom resuspension layer (25-50 m thick) below the 175-180 m base of a particle-free zone in both basins. Beam attenuation due to particles (Cp) increased from 0.1 m-1 at 175m to >0.5m-1 at 182m in Wilkinson Basin, with the same increase in attenuation observed between 180m and 210m in Jordan Basin. Quantitative effects of particle input from the resuspension layer to the 250m traps are being examined using a variety of chemical trace analyses applied to trap-collected particulate and bottom sediment samples. Additionally, an assessment of the impact of heavy bottom trawling activity on particulate organic matter flux and regeneration in Wilkinson Basin is being pursued.

(Key Words: biogeochemical fluxes, particulate nutrient cycling)

Monitoring Biodiversity: Protocol Development for Marine and Estuarine Environments

Gerhard W. Pohle
Atlantic Reference Centre, Huntsman Marine Science Centre, St. Andrews, New Brunswick, E0G 2X0, Canada
506-529-1203 arc@sta.dfo.ca

The Steering Committee of the Quoddy Region Ecological Science Cooperative (ESC) at the Huntsman Marine Science Centre (HMSC) recently struck a working group charged with developing protocols for the monitoring of marine and estuarine biodiversity. The mandate is to develop nationally relevant protocols for conducting comparable biodiversity assessment studies at or above the species level, aimed at detecting long term trends within ecosystems. Scientists from various institutions have developed draft guidelines for different groups of organisms characteristic of particular habitats. These include benthic invertebrates (soft and hard bottom, intertidal and subtidal), seabirds, fish, mammals, phytoplankton, zooplankton, parasites, and seaweeds. Draft documents were submitted to the Ecological and Monitoring Assessment Network (EMAN) of Environment Canada for comment and further development. The objective in developing these protocols is to provide guidelines so that any monitoring done by different individuals or groups at different times and localities can be appropriately compared, and the differences or changes recorded can be interpreted as such and do not merely reflect differences in the methodology used in monitoring.

(Key Words: biodiversity, monitoring, marine protocols)

Linkages of the Early Life History Stages of Sea Scallops with the Physical Environment in Southwestern New Brunswick

Shawn M.C. Robinson, Jim D. Martin, Ross A. Chandler, G. Jay Parsons
St. Andrews Biological Station, Dept. Fisheries and Oceans, St. Andrews, N.B., E0G 2X0, Canada
506-529-8854 robinson@wolves.sta.dfo.ca

The distribution patterns of sea scallop larvae in the Passamaquoddy Bay/Quoddy region of the Bay of Fundy have been inferred from the settlement of scallops in standard Japanese onion bags at 25 stations set in a uniform two nautical mile grid array. The onion bags have been deployed annually in August and recovered in December since 1989. Sampling of temperature/salinity profiles has also occurred during this period at all the stations on a monthly basis. In addition, horizontal transects have been done for chlorophyll a within Passamaquoddy Bay. The results indicated scallop larvae appear to be distributed by water currents in a very consistent fashion from year to year and that although the actual numbers may vary annually, the relative size of the animals are consistent between stations (i.e. the same group of stations always have the largest spat). The patterns of distribution in the scallop spat are consistent with the physical and other biological information, such as the chlorophyll a data. Our interpretation of the data suggests the scallop larvae resulting from the summer spawning are advected into the upper part of Passamaquoddy Bay where a gyre is acting as a retention area. The larvae in this area experience higher water temperatures and also higher potential food levels based on the chlorophyll a surveys and the stratification of the water column which occurs when the larvae are present. We hypothesize, the settling larvae then use other hydrodynamic mechanisms to move them to appropriate benthic areas which are suitable for settlement.

(Key Words: scallops, larval drift, settlement, Bay of Fundy)

Correlation Between Land Use Patterns and Flux of Dissolved Trace Metals in the Charles River Basin, a Small Urban Watershed

Elva Wohlers Romanow, Gordon T. Wallace
Environmental Sciences Program,
University of Massachusetts-Boston,
100 Morrissey Blvd., Boston, MA 02125
617-287-7464 1533eroma@umbsky.cc.umb.edu

Fluxes of dissolved copper, zinc, lead, cadmium, nickel, aluminum, and iron were estimated at different points in the Charles River watershed. Changes in concentration and flux were compared to changes in land use from the headwaters to the mouth of the river which enters Boston Harbor about 120 km downstream. Land use in the watershed can be divided roughly into two different major uses, a mixture of residential and undeveloped land in the upper reaches of the river and the more densely populated, urbanized lower part of the watershed. Concentrations of dissolved metals increased by a factor of between 2 to 3 for all metals between the headwaters in Echo Lake, used as a drinking water supply for the town of Milford, and the mouth of the river with the exception of lead and aluminum. Lead concentrations increased by about a factor of 30 downstream while aluminum concentrations remained about the same throughout the course of the river. Metal fluxes,

normalized to river flow, increase abruptly at the transition between the two land use patterns. The relative importance of non-point and point discharges of these metals to the Charles River watershed will be discussed.

(Key Words: trace metals, land use, flux, river, watershed)

Diet of Key Fishes Collected in the Gulf of Maine During NEFSC Bottom Trawl Surveys Conducted from 1981-90

Rodney A. Rountree
NMFS, Northeast Fisheries Science Center,
166 Water St., Woods Hole, MA 02543
508-495-2340 rrountre@whsun1.wh.whoi.edu

Food habits data were collected 20,245 stomachs of 39 species of fishes and two squids during standard bottom trawl surveys of the Gulf of Maine from 1981-90. The 10 most frequently sampled species included: Silver hake, white hake, spiny dogfish, Atlantic cod, red hake, pollock, thorny skate, Acadian redfish, sea raven, and longhorn sculpin. Silver hake fed on Euphausids, pandalids and other crustaceans and other silver hake. White hake had a similar diet, but was more piscivorous. Spiny dogfish fed on ctenophors, euphausids, pandalids, clupeids and cnidarians. Atlantic cod fed on shrimps, polychaets, Ophiuroids, crabs, sand lance and silver hake. Red hake fed on shrimps, euphausids, polychaets, and amphipods.

(Key Words: Gulf of Maine, fish diets, food chain).

Fish Predator Guilds for Georges Bank Based on Food Habits Data Collected During NEFSC Bottom Trawl Surveys from 1981-90

Rodney A. Rountree
NMFS, Northeast Fisheries Science Center,
166 Water St., Woods Hole, MA 02543
508-495-2340 rrountre@whsun1.wh.whoi.edu

Food habits data collected on Northeast Fisheries Science Center groundfish surveys between 1981 and 1990 were analyzed to categorize abundant fish species into feeding guilds. Fishes examined included several species of Gadids, Pleuronectids, and elasmobranchs. To take into account expected large ontogenetic changes in diet, each species was divided into 10 cm size classes, which were analyzed separately. Most species clustered into two or more distinct intra-specific groups based on size, supporting the concept of "ecological species". Predator guilds bore little relation to taxonomic grouping, but were strongly influenced by predator size, habitat (pelagic, semi-pelagic, and benthic), extent of piscivory, and prey size. The identification of predator guilds on Georges Bank, is an important first step in ongoing studies of competitive interactions among fishes in the Georges Bank groundfish community.

(Key Words: Georges Banks, guilds, prey suites, predator-prey, food habits).

Time-Resolved, Laser-Induced Fluorescence for the Detection of Polycyclic Aromatic Hydrocarbons in the Marine Environment

Steven M. Rudnick, Robert F. Chen
UMass-Boston, Environmental Sciences Program,
100 Morrissey Blvd. Boston, MA 02125-3393
617-287-7448 7001srudn@umbsky.cc.umb.edu

Laser-induced fluorometry can be used to detect organic matter in the marine environment. The majority of fluorophores in the 390 to 510 nm band are humic substances which have fluorescent lifetimes under 4 nsec. By time gating the fluorescence measurement, substances such as polycyclic aromatic hydrocarbons (PAH) with much longer lifetimes can be studied. We have developed a laser-induced, time-resolved spectrofluorometry system capable of in-situ, real-time detection of these fluorophores. The system consists of a pulsed nitrogen laser focused onto a 0.4 mm diameter silica clad silica optical delivery fiber, and a concentric ring of 9 x 0.2 mm diameter collection fibers delivering the emission radiation to a/meter imaging spectrograph whose output is focused on the input lens of a gated, intensified 1024 x 256 pixel charge-coupled camera.

We have deployed this system in San Diego Bay, Georges Bank, the Mid-Atlantic Bight and Boston Harbor. In each of these deployments we have been able to detect increased long-lived fluorophores in areas where anthropogenic influence would be expected. By utilizing the spectral and time resolution capabilities of our system, it is possible to detect and quantify individual PAH such as pyrene and fluoranthene in the Boston Harbor environment. Real-time detection of PAH in Boston Harbor allows identification of point sources, determination of seasonal trends, mapping of PAH distributions and estimation of the contribution of contaminated sediments as a source of PAH.

(Key Words: fluorescence, PAH, contaminants)

Seasonal Distribution of Finfish in the Coastal Western Gulf of Maine Relative to Bottom Water Temperatures, Sediment Grain Size, Sediment Carbon and Nitrogen Levels, and the Fishery for Northern Shrimp

Daniel F. Schick
Maine Dept. Marine Resources,
W. Boothbay Hbr., ME 04575
207-633-9500 mrdschi@state.me.us

Michael Brown, Mark Lazzari, Sally Sherman
Maine Dept. Marine Resources,
W. Boothbay Hbr., ME 04575
207-633- 9500 mrmbrow@state.me.us,
mrmlazz@state.me.us mrssher@state.me.us

Inshore (<50F) winter shrimp fishing grounds between Frenchman's Bay and Ipswich Bay have traditionally had little bycatch compared to deeper tow locations, but little is known about seasonal inshore finfish distribution. This distribution was studied relative to a variety of habitat parameters. Sampling was conducted quarterly from May, 1992 through March, 1993 across a grid of six transects east to west and four depths between 20 and 60 fathoms. Sampling was continued for three of these transects during four summer months in 1993 and four winter months in 1994. Factorial ANOVA, or if necessary, the Kruskal Wallace test was used to assess the distribution of eleven species of finfish. The distribution was also tested against bottom temperature and sediment grain size, carbon and nitrogen content.

Over the four initial cruises in 1992-93, location east to west accounted for 25 significant differences in distribution with 15 showing greater numbers to the west, 9 to the east and only one centrally located. Depth accounted for 15 differences with 9 showing greater numbers at the deepest stations and 3 at the shallowest stations. Eight significant interactions between location and depth showed strong localization of some species. For the 11 species, the total fish/tow was highest in May (37,666) and lowest in March (7,732), while shrimp were highest in January (N=52,282) and lowest in September (4,116).

The sampling in 1993-94 showed similar differences in distribution between summer and winter. The distribution of finfish and shrimp relative to sediment grain size and sediment carbon and nitrogen mirrored the depth-related differences as the shallower stations had higher percentages of sand and lower levels of carbon and nitrogen than the deeper stations.

(Key Words: finfish, shrimp, sediment, temperature, distribution).

A Survey of PCB Congeners in Winter Flounder Liver Tissue from Coastal Massachusetts and Georges Bank

Jack P. Schwartz
Division of Marine Fisheries, Cat Cove Marine Laboratory, 92 Fort Ave., Salem, MA, 01970
617-727-3958 x122 jschwartz@state.ma.us

Nina M. Duston
617-727-3958 x121 nduston@state.ma.us

Carol A. Batdorf
617-727-3958x119 cbatdorf@state.ma.us

William Sullivan
617-727-3958x107 wsullivan@state.ma.us

Chad M. Hutcheson
203 Laverne Ave., Baltimore, MD, 21227

Concentrations of eighteen PCB congeners (included in NOAA protocol) were measured by gas chromatography in winter flounder (Pseudopleuronectes americanus) livers collected in Massachusetts Bay near the MWRA Future Outfall site, Broad Sound, Deer Island Flats in Boston Harbor, eastern Cape Cod Bay, Vineyard Sound, outer New Bedford Harbor, and Georges Bank. Mean total concentrations at each site as ppb (ng/g dry wt.) decreased in the following order:

New Bedford (16000), Deer Island Flats (5200) MWRA Future Outfall (3400), Vineyard Sound (2400), Broad Sound (2000), eastern Cape Cod Bay (600), and Georges Bank (120). The proportion of congeners in liver samples (normalized to BZ# 138) was different between geographical regions. Congeners dominant in all samples were BZ# 118, 153/105, and 138, regardless of location. Flounder livers from the Massachusetts Bay region (Deer Island, Broad Sound, MWRA Future Outfall) had similar congener proportions and more BZ# 187 than liver samples from other regions. Liver samples from Vineyard Sound were similar to New Bedford Harbor samples. The samples from eastern Cape Cod Bay and Georges Bank were similar and contained greater proportions of BZ# 8, 18, 28 and 101 compared to liver samples from all other areas. Information on the source(s) of PCB exposure from land and atmosphere over large geographical areas of the Gulf of Maine is needed to account for regional differences in PCB congener distributions. It is important to quantify and report PCB congeners when reporting total PCB concentrations in fish tissues and all other environmental samples.

(Key Words: Polychlorinated biphenyls, winter flounder, congeners, Massachusetts, Gulf of Maine)

Macro Invertebrates Associated with *Ascophyllum Nodosum* (L.) Le Jolis Canopy in the Gulf of Maine and the Impact of Harvesting on the Canopy

Glyn J. Sharp, R. Semple, I. Barkhouse
Fisheries and Oceans Canada, P.O. Box 550,
Halifax, NS B3J 2S7 Canada

Ascophyllum nodosum assemblages sampled at high tide in the summer from the Bay of Fundy had a minimum of 42 associated macro invertebrate species. Total numbers of macro invertebrates averaged 253±201 to 346±322 $1000g^{-1}$ wet weight of plant biomass. Recruitment of early life stages of invertebrates such as *Mytilus edulis* spat increased abundance at some sites by a factor of 10. The total abundance of invertebrates was realated to the biomass of *A. nodosum* (R^2 .58 to .62). This relationship was largely due to the association of plant biomass with gatropods, particularly the dominant gastropod *Littorina obtusata.* Time of submergence affected the diversity of the macro invertebrate assemblage, gastropoda decreased with tide level and crustaceans increased with tide level. The abundance of macro-invetebrates 1000 g^{-1} of *A. nodosum* clumps was not correlated with stand biomass or density of clups. The abundance and species of immigrating invertebrates was strongly related to surrounding substrate type. Harvesting changes the population structure of a *A. nodosum* stand either reducing the modal length or changing bimodal length distributions to unimodal as well as reducing the standing crop up to 17%. The implications of these changes on the abundance and diversity of associated canopy invertebrates are evaluated for the short and long-term.

(Key Words: Bay of Fundy, Ascophyllum nodosum, invertebrates, harvesting)

Coupled Biological and Physical Modeling of Red Tide Organisms in the Western Gulf of Maine

Richard P. Signell
United States Geological Survey,
Woods Hole, MA 02543
508-457-2229 rsignell@usgs.gov

Peter S.J. Franks
Scripps Institution of Oceanography,
La Jolla, CA 92093
619-534-7528, pfranks@ucsd.edu

Donald M. Anderson
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
508-457-2000, danderson@whoi.edu

Derek A. Fong
MIT/WHOI Joint Program in Oceanography, Woods Hole Oceanographic Institution
Woods Hole, MA 02543
508-457-2000 dfong@whoi.edu

W. Rockwell Geyer
Woods Hole Oceanographic Institution,
Woods Hole, MA 02543
508-457-2000 rgeyer@whoi.edu

Bruce Keafer
Woods Hole Oceanographic Institution,
Woods Hole, MA 02543
508-457-2000 bkeafer@whoi.edu

Theodore C. Loder III
University of New Hampshire, Durham, NH
603-862-3151 ted.loder@unh.edu

In the western Gulf of Maine, "red tide" blooms (high concentrations of the toxic dinoflagellate Alexandrium tamarense) are often associated with a buoyant coastal plume formed by the outflow of several large river systems. The ability to realistically simulate these blooms is a major goal of environmental managers in this region, but presents significant technical and scientific challenges. Extensive field surveys were conducted in the spring of 1993 and 1994 to map the spatial and temporal patterns of currents, nutrients, salinity, temperature and cell concentrations over a roughly 200 x 50 km (alongshore and cross-shore) domain. These surveys yield unprecedented levels of information on which to calibrate and test a numerical model of red tide transport and growth.

Using the Blumberg-Mellor hydrodynamic model coupled with a simple cell growth equation, we are conducting a suite of simulations varying the location and timing of cell introduction, offshore boundary conditions and representations of vertical mixing. The model is a limited to the western Gulf of Maine and is driven at the open boundaries by a combination by observations and Gulf-scale model output (Lynch and Naimie, 1993; Lynch, Holboke and Naimie, 1996). Results to date show that the timing and location of the source are crucial for obtaining realistic magnitudes of cell concentrations. They also reveal that realistic modeling of plume behavior may be limited by the ability to correctly represent horizontal and vertical mixing processes and to specify realistic open boundary conditions.

(Key Words: modeling, red tide, circulation)

Assessing Benthic Impacts of Fish Farming with an Expert System Based on Neural Networks

Martin Baptist
Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, NS, Canada B2Y 4A2,
Baptist@hed.bio.dfo.ca

William Silvert
Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, NS, Canada B2Y 4A2
902-426-1547 Silvert@scotia.dfo.ca

Dror Angel
Water Quality Research Group, National Center for Mariculture, POB 1212, Eilat 88112, Israel,
Angel@agri.huji.ac.il

Peter Krost
CRM, Zum Tamberg 2, D-24247 Mielkendorf, Germany
CRM.Office@t-online.de

Geochemical profiles provide valuable data on the benthic impacts of fish farming and other human activities, but the interpretation of these data is a complex process requiring scientific sophistication and understanding of benthic processes. Neural networks were used to simulate the impact-assignment process in an effort to develop an expert system that does the same analysis. The case study was based on data from an investigation of the benthic impact of a fish farm in the Red Sea (Angel, Krost and Silvert, submitted). Sediment profiles for loss on ignition (LOI) data were used to classify environmental impacts in terms of fuzzy sets "Nil", "Moderate", "Severe" and "Extreme". A neural network was trained to produce a set of assessments expressed as fuzzy memberships directly from sediment profile data, by providing it with a set of examples of input profiles and the corresponding output fuzzy set memberships. This results in a non-linear model of benthic impacts with the raw data of the sediment profiles as input. A trained neural network is able to come up with results comparable to those of a scientific expert.

(Key Words: Neural network, fuzzy logic, expert system, sediment profile, benthic impact).

Toxic Contamination in *Mytilus Edulis* at Gulf of Maine Sites Monitored by Gulfwatch

John Sowles
Maine Department of Environmental Protection,
State House 17, Augusta, ME, 04333
207-287-6110 John.Sowles@state.me.us

Gareth Harding
Department of Fisheries and Oceans,
Bedford Institute of Oceanography, P.O. Box 1006,
Dartmouth, NS, B2Y 4A2, Canada
902-426-2672 Gareth.Harding@sfnet.dfo.ca

Stephen H. Jones
Department of Natural Resources,
Jackson Estuarine Laboratory, University of
New Hampshire, Durham, NH, 03824
603-862-2175 shj@christa.unh.edu

Peter Hennigar
Environment Canada,
Bedford Institute of Oceanography,
P.O. Box 1006, Dartmouth, NS, B2Y 4A2, Canada
902-426-6191 hennigarp@ns.doe.ca

Robert Crawford
Nova Scotia Department of Fisheries,
P.O. Box 2223, Halifax, NS B3J 3C4, Canada
902-424-0351 crawford@gov.ns.ca

The presence of toxic compounds in the Gulf of Maine is a transboundary issue with many poorly understood ramifications. Gulfwatch is a program in which blue mussels, *Mytilus edulis*, have been used successfully for 5 years as sentinel species for habitat exposure to toxic contaminants. Mussels were collected at over sixty subtidal, protected sites in all five jurisdictions on a three year rotating basis for long-term analysis of contaminants. Short-term biological responses and toxic accumulation were determined using caged mussels deployed at a subset of sites for 60 days. Tissue was analyzed for 10 heavy metals, 17 chlorinated pesticides, 24 polyaromatic hydrocarbons, and a suite of PCB congeners. Biological responses were determined by growth and condition index measurements. The results showed a southward trend of increasing organic contaminant concentrations, and in some cases, heavy metals. Contaminant concentrations were higher than expected at some sites assumed to be clean sites. Human health issues due to metal and organic contamination were found to be minimal. Growth patterns and biological responses showed few consistent trends. General trends reflect major regional and local point and nonpoint sources of contaminants. The results provide unique, Gulf-wide information that can help focus efforts to reduce toxic contaminant loading.

(Key Words: toxic organic compounds, heavy metals, environmental exposure, blue mussels, multijurisdictional monitoring program)

The Merrimack River: An Important Source of Contaminants to the Gulf of Maine

Marie Studer
Massachusetts Bays Program,
100 Cambridge Street, Boston, MA 02202
(617) 727-9530 x405 mstuder@state.ma.us

Gordon Wallace
University of Massachusetts-Boston,
100 Morrissey Blvd., Boston, MA 02125
(617) 287-7447 wallace@umbsky.cc.umb.edu

Jerry Cura
Menzie-Cura and Associates, One Courthouse Lane,
Suite 2, Chelmsford, MA 01824
(508) 453-4300 menziecura@aol.com

The Merrimack River is the fifth largest river source to the Gulf of Maine. However, because of its location in central New Hampshire and Massachusetts, it is more heavily populated and industrialized than larger watersheds in Maine and Canada. Thus, it may have a greater impact on the water quality of the nearshore region due to elevated concentrations of contaminants observed in the river and the correspondingly high fluxes. Two separate studies were conducted to determine the importance of the Merrimack River as a source of metals and organic contaminants to the Gulf of Maine and Massachusetts Bays ecosystems.

A two-year study of the Merrimack River was undertaken between 1989 and 1991 to determine the geochemical behavior of selected metals in the river system and the anthropogenic influence on water column metal concentrations, distribution and fate. Changes in metal concentration and fluxes to the Merrimack Estuary under varying flow regimes and seasonal conditions were observed. The magnitude of the spring transport, and the large percentage of metals in the dissolved form throughout the year, indicates that metals may be efficiently transported to the Gulf of Maine and could significantly impact metal concentrations in the near-shore region.

In 1992 and 1993 another study was conducted by Menzie-Cura and Associates for the Massachusetts Bays Program to determine the flux of organic contaminants from the Merrimack to Massachusetts Bay. It was estimated that the Merrimack River could contribute as much as 8% of the estimated total PAH loadings to Massachusetts Bay. Concentrations of PCBs and pesticides were generally below detection limits in the water column, therefore flux estimates for these compounds were not determined.

(Key Words: Merrimack River, metals, PAHs, Massachusetts Bay).

Internal Wave Processes in the Gulf of Maine

David W. Townsend, Neal R. Pettigrew, Peter J. Brickley, John Wallinga, Fei Chai, Andrew Thomas
Dept. Oceanography, University of Maine, Orono, ME 04469-5741 davidt@maine.maine.edu

Charles S. Yentsch, Michael E. Sieracki, Christopher Garside, Douglas Phinney, Jeffrey Brown
Bigelow Laboratory for Ocean Sciences, P.O. Box 475, W. Boothbay Harbor, ME 04575

Recognition of the presence of internal waves in the Gulf of Maine, and their possible importance as agents of vertical mixing and nutrient fluxes into surface waters of the offshore Gulf prompted an interdisciplinary field, modeling and remote sensing study by a team of investigators from the University of Maine and the Bigelow Laboratory. With funding from the Office of Naval Research, we have conducted simultaneous ship-board and moored sampling to observe internal wave processes in the western Gulf during late summer of 1995, a period of strong stratification and depletion of nutrients in the euphotic zone. A dense vertical array of moored temperature and salinity sensors and a 300 kHz ADCP, which sampled the upper 65 meters of the water column, was deployed at the 200 m isobath of Wilkinson Basin. During the 30 day deployment period, an intensive 5 day hydrographic survey was performed to capture details of the spatial and temporal hydrographic, chemical and biological variability associated with the passing internal waves. We observed a rich and energetic mixture of internal disturbances representing both low mode internal tidal waves and higher frequency waves. We also observed large (20 m) non-linear solitary waves producing concurrent vertical displacements of the fluorescence and turbidity maxima associated with a deep chlorophyll maximum. Our preliminary results suggest strongly that vertical mixing by internal waves can make a measurable contribution to the Gulf's nutrient budget. We present details of specific results to date from our suite of physical, chemical and biological measurements.

(Key Words: Gulf of Maine, internal waves, vertical mixing, nutrient fluxes)

Scale of Changes of the Rockweed *Ascophyllum Nodosum* (L.) Le Jolis Population Structure and Biomass Caused by Harvesting in Southern New Brunswick

Raul A. Ugarte
Acadian Seaplants Ltd.,
P.O. Box 90, Pennfield, NB, Canada
506-849-2773 rugarte@atcon.com

The harvestable biomass of *Ascophyllum nodosum* in Southern New Brunswick has been estimated in 140,000t. Under a co-management agreement, a license was granted to Acadian Seaplants Ltd. in 1995, for a 10,000t annual pilot scale harvest of rockweed.

The assessment of the resource, based on ground truthing and aerial photographs, provides accurate information on biomass distribution, density, plant size, cover and area. The error measurement for area is less than 1%. This information, obtained for every bed, provides a strong data base to develop a three year management strategy for each sub-sector of the resource.

An ongoing monitoring program assesses cutting height, changes in population structure, plant mortality, and growth. The cutting height averages over 35 cm. with the existing harvesting gear. The impact of harvesting on the habitat is assessed by monitoring the catch and using experimental studies.

(Key Words: rockweed, harvest, management, Ascophyllum nodosum)

New Imagery of Seabed Environments in the Stellwagen Bank Region, Gulf of Maine

Page Valentine, William Danforth,
Edwin Roworth, Sara Stillman
U.S. Geological Survey, Woods Hole, MA 02543
508-457-2239 pvalentine@usgs.gov

John Hughes-Clarke
University of New Brunswick,
Fredericton, N.B., Canada E3B 5A3

The U.S. Geological Survey and the National Oceanic and Atmospheric Administration, in cooperation with the Canadian Hydrographic Service and the University of New Brunswick, have completed a multibeam topographic and sidescan sonar survey of the Stellwagen Bank National Marine Sanctuary and adjacent areas (1100 nm2), including the Massachusetts Bay Disposal Site (MBDS) off Boston. Seabed morphology in the mapped area is a result of: glacial erosion of preexisting rocks and sediment; deposition of glacier-borne sand and gravel; and later deposition of mud eroded from land and shallow coastal environments. These processes produced a rugged sea floor of sandy and gravelly banks separated by muddy basins. Principal geomorphic regions are: (1) large, relatively deep (80-100 m water depth) coastal basins (Stellwagen and Scantum Basins) bounded on the east by (2) large, elongate, shallow (20-50 m) banks (Stellwagen Bank, Jeffreys Ledge); (3) regions of small knolls (60-90 m) separated by small, deeply-incised basins (150-200 m); and (4) a ramp of glacial sediment (70-120 m) grooved by ancient ice berg scours that extends from Jeffreys Ledge and Stellwagen Bank eastward into the Gulf of Maine. Modern sediment movement principally is confined to the tops of shallow banks where storm currents from the northeast transport sand onto their western flanks to depths of 50-60 m. Glacial and modern processes have produced diverse sedimentary environments in the Stellwagen Bank region, including: storm-driven sand sheets and bedforms; linear shell deposits; gravel beds; boulder fields; muddy sand; and mud. Imagery of the MBDS reveals the distribution of individual deposits and large mounds of dredged material, sunken vessels, and piles of rock debris disposed in 1992 and 1993 and now inhabited by lobsters and redfish. Maps showing seabed features and sediment texture, supported by video and photo imagery of fauna and habitats, provide a valuable base for conducting environmental and fisheries-related research in the region.

(Key Words: Stellwagen Bank, Gulf of Maine, topography, sidescan sonar, seabed environment)

The Atlantic Reference Centre — Aquatic Collections Repository and Scientific Service Center for the Canadian Atlantic

Lou Van Guelpen
Atlantic Reference Centre, Huntsman Marine Science Centre, St. Andrews, NB E0G 2X0 Canada
506-529-1203 arc@sta.dfo.ca

The Atlantic Reference Centre (ARC) is an important component of the fishing and aquaculture industries in Atlantic Canada and the Gulf of Maine. The ARC, a joint program of the Huntsman Marine Science Centre (HMSC) and the Canadian Department of Fisheries and Oceans (DFO), is a systematics and ecological research laboratory and a repository for aquatic biota. Formed in 1984 as a consolidation of existing HMSC and DFO collections, the ARC has grown into the regional museum for aquatic organisms in Atlantic Canada. Holdings include algae, invertebrates, and fishes ranging from Baffin Island to Georges Bank and fresh water to the deep sea. Strengths include deepsea crustaceans, parasites of fishes, mesopelagic fishes, and the largest collection of fish eggs and larvae in North America. In addition to the collections, the ARC performs the functions of identification service, scientific advice, training and teaching, research, and development and dissemination of technical literature.

The collections and resources of the ARC are of major importance to the scientific interests of the Gulf of Maine. Ichthyoplankton from DFO's annual Georges Bank Larval Herring Survey is processed and curated at the ARC. Both ichthyoplankton and zooplankton samples have been processed for the Maine Department of Marine Resources. ARC staff advise Maine government agencies on diagnosis and treatment of fish diseases, especially sea lice on Atlantic salmon. The ARC will collaborate with the Maine Department of Environment on freshwater insect community analyses. Regional effects on benthic communities caused by organic enrichment, such a salmonid aquaculture, are being investigated by the ARC in Passamaquoddy Bay. Results will be of prime interest to nearby Maine fish farmers. Biodiversity monitoring protocols for perturbations on marine habitats are being developed and coordinated at the ARC for Environment Canada. These protocols also will be relevant to the Gulf of Maine, which shares a common marine ecozone and ecoprovince with Canada's Bay of Fundy and Scotian Shelf.

Dissolved Organic Carbon Fluxes in Massachusetts Bay

P. Vlahos, R.F. Chen
Environmental Sciences Program,
University of Massachusetts Boston,
100 Morrissey Blvd., Boston, MA 02125
G5128EVLAH@umbsky.cc.umb.edu
CHENR@ umbsky.cc.umb.edu

Massachusetts Bay is semi-enclosed estuary with high productivity and significant freshwater inputs. These inputs are sources of both particulate and dissolved organic carbon (POC and DOC). Ultimately the organic carbon produced may be buried in coastal sediments, recycled within the water column or transferred to the open oceans. Vertical profiles of beam attenuation show distinct areas of nepheloid suspensions in bottom waters of the bay. Characterization of this layer may improve our understanding of organic carbon contaminant fluxes.

Dissolved Organic Carbon (DOC) profiles were measured at 8 stations throughout Massachusetts Bay to obtain both vertical and horizontal distributions. Measurements were taken every four to five weeks beginning in May, 1996. Samples were analyzed using CHN, DOC/POC, chlorophyll and UV fluorescence. The profiles provide spatial and temporal DOC coverage of inputs at Cape Ann, freshwater loadings and outputs at Race Point Cape Cod.

Measurements are used in a simple mass transport model to obtain a net DOC balance for Massachusetts Bay. The role of DOC in controlling the distributions of contaminants that may sorb to it will be addressed. DOC fluxes can be estimated and used to determine whether DOC is an important link in the global carbon cycle and our understanding of chemical fates in the coastal environment.

(Key Words: Massachusetts Bay, DOC, POC, carbon cycle, nepheloid layer).

Is "Real Time" the Key to Understanding How Temperature Influences Recruitment in the American Lobster?

S. L. Waddy, D. E. Aiken
Biological Station, St. Andrews, N.B. EOG 2XO Canada
506-529-8854 s_waddy@bionet.bio.dfo.ca

At first glance lobsters respond to seawater temperature in a straightforward manner: they grow faster, mature at a smaller size and produce eggs earlier in the season in warmer areas than colder ones. However, temperature regulation of biological cycles is complex and there is evidence the thermal requirements for growth and reproduction are not cumulative (as in degree-days) but a combination of threshold and cumulative phenomena. Simple analysis of degree-days can be misleading. Response to temperature is influenced by time of year, temperature history, and whether a threshold temperature has been reached. Dramatic physiological changes, that affect how larvae, juveniles and adults respond to temperature, occur at both the autumnal equinox and the winter solstice, and probably the spring solstice and summer equinox as well. With the change of seasons, temperatures inadequate for growth and reproduction become favorable and time required for larval development and ovarian maturation at a given temperature can be reduced by as much as 50%. Interestingly, environmental control of lobster biological cycles is not unlike that in insects, birds and other animals, suggesting the mechanisms may be widespread. Because of the effect of time of year on temperature requirements, it is becoming necessary to re-evaluate conclusions drawn from earlier studies and to rethink perceptions of preferred temperature environments and conditions required for molting and egg production. This knowledge has already explained previously puzzling phenomena such as why lobsters do not enter premolt in the autumn, even though temperatures are more favorable than in the spring, and why lobsters have developed a

variety of growth and reproductive strategies to cope with latitudinal and seasonal variations in temperature. Estimates of yield and egg production in lobster stocks use models that take into account growth rates, size at maturity, and frequency of spawning, all of which vary with temperature. Information now being obtained on the nature of the temperature control mechanisms should improve our ability to model growth, egg production and recruitment in this stock.

(Key Words: American lobster, temperature, growth, reproduction)

Metal Distributions in Massachusetts and Cape Cod Bays – Sources, Transport and Fates

Gordon T. Wallace, Christian Krahforst
Environmental Coastal and Ocean Sciences Program,
University of Massachusetts at Boston
100 Morrissey Blvd., Boston, MA 02125
617-287-7447 wallace@umbsky.cc.umb.edu

Revendra Ika, James P. Shine
Dept. of Environmental Health,
Harvard School of Public Health,
665 Huntington Ave., Boston, MA 02115

Marie M. Studer
Massachusetts Bays Program,
Executive Office of Environmental Affairs,
100 Cambridge St., Boston, MA 02202

Over the last decade there has been a substantial increase in our quantitative knowledge of the sources of metals, both point and non-point, to Massachusetts and Cape Cod Bays as well as knowledge of the processes affecting the transport and retention of metals within the Bays' environment. Point source discharges from sewage treatment facilities and atmospheric deposition inputs are of sufficient magnitude to have significantly altered water column and sediment concentrations in the Bays, especially in the northwest part of Massachusetts Bay and Boston Harbor. Large scale circulation patterns in the western Gulf of Maine and in Massachusetts and Cape Cod Bays make Massachusetts Bay particularly sensitive to anthropogenic inputs from both local and coastal Gulf of Maine anthropogenic sources of contaminants. Elevated surface-sediment water column concentrations of selected metals in Massachusetts and Cape Cod Bays are consistent with that predicted based on observed metal concentrations in Boston Harbor and model predicted transport of Harbor water into Massachusetts and Cape Cod Bays. Removal of metals to the underlying oxic surface sediments appears to be largely controlled by sorption equilibrium between dissolved metal concentrations in the overlying water column and sedimentary organic matter. The use of a simple partition model based on dissolved metal concentrations, surface-sediment organic carbon concentrations, and empirically based apparent sorption constants, while not rigorously defined, has practical value in the prediction of surface sediment concentrations for a number of metals.

(Key Words: metals, water column, sediments, sorption, Gulf of Maine)

The Occurrence and Comparative Geochemistry of Silver and Other Selected Metals in the Gulf of Maine

Christian F. Krahforst and **Gordon T. Wallace**
Environmental Coastal and Ocean Sciences Program,
University of Massachusetts Boston
100 Morrissey Blvd., Boston, MA 02125
617-287-7464 7039ckrah@umbsky.cc.umb.edu

The geochemistry of Ag along with the comparative geochemistries of Cu, Zn and Pb have been investigated in the upper 60m along a transect extending off the southern most portion of Maine in June of 1996. The purpose of this study is to provide a baseline assessment of Ag and other metals concentrations in the Gulf of Maine prior to the influence of discharges from the Merrimack River and Boston's waste effluent.

In general, dissolved silver concentrations decreased with distance offshore. The bulk of total silver resided in the operationally defined "dissolved" (0.4 µm filter-passing)fraction (82 ± 8%). Mean dissolved silver concentrations were 12 ± 6 pMol kg^{-1}. Using the mean total Ag concentration and estimates of the advective transport of Gulf of Maine water into Massachusetts Bay, the flux of Ag from the Gulf of Maine is about 25% of the Ag flux originating from the waste treatment facility of Boston.

Bottom Boundary Layer Structure on the Southern Flank of Georges Bank During Late Winter

Sandra R. Werner
MIT/WHOI Joint Program inOceanography, Woods Hole Oceanographic Institution, MS 21, Woods Hole, MA 02153
508-289-2802 sandra@sound.mit.edu

Robert C. Beardsley, Steven J. Lentz, James H. Churchill, John H. Trowbridge, William J. Williams
All at: WHOI, PO/AOPE Dept., MS 21, Woods Hole, MA 02153
508-289-2536 rbeardsley@whoi.edu

The bottom boundary layer structure on the southern flank of Georges Bank is investigated during vertically homogeneous conditions. Velocity data taken by benthic acoustic stress sensors (BASS) and vector-measuring current meters provide measurements covering the entire water column between 0.28 m above the bottom and the sea surface. Tidal analysis reveals that the M_2 velocities are on average four times the subtidal flow, with the clockwise rotating component contributing $\approx$ 80% to the total current speed. Boundary layer thicknesses of the M_2 rotating components are found to scale as $\delta^{\pm} \approx 0.35\ \kappa \bar{u}_* /(\sigma \pm f)$, where σ is the frequency of the M_2 tide, and $\bar{u}_*$ is the time-mean friction velocity. With the clockwise rotating component being dominant, the total boundary layer thickness is described by $\delta \approx \delta^- \approx 40$ m. Friction velocities derived from best-fit logarithmic profiles to BASS data are in good agreement with stress magnitudes based on integrated velocity defects. Data suggest the subtidal boundary layer height to scale as $\delta^{ST} \approx 0.27\ \kappa \bar{u}_* / f$, indicating that the parameterization of subtidal and tidal boundary layer thicknesses differs according to the time scales on which temporal variations occur. Numerical results for the tidal flow using a one-dimensional, two-layer model with vertical mixing coefficient $K = \kappa \bar{u}_* z$ in the sublayer $z \le l$ and $K = \kappa \bar{u}_* l$ in the rest of the water column suggest $l = 0.1\ \delta$ as a reasonable choice for observed velocities, bottom stresses, and boundary layer transports to be reproduced closely. Measured data indicate the scale height $0.1\ \delta$ to describe the thickness of the logarithmic region, in agreement with results from earlier studies of steady and rectilinear flows. (Key Words: Georges Bank, bottom boundary layer, data analysis, numerical modeling, vertical mixing)

Assessment: The First Step in Integrated Coastal Msanagement

Louise White
Fisheries and Oceans, Bedford Institute of Oceanography, Dartmouth, Nova Scotia

Frank Johns
TAS Editorial Services Ltd., Halifax, Nova Scotia

The focus of a marine regional assessment is to present a broad synthesis of the scientific knowledge about a marine system. It discusses the extent of anthropogenic modifications to the marine environment, points out principal uncertainties that hinder our understanding of the marine environment, and identifies important regional environmental issues. The most useful form of an assessment is one that can serve multiple audiences, non-specialists as well as professional scientists. Both groups would benefit from understanding a regional ecosystem at the largest spatial and temporal perspective possible.

There are two main international standards for producing such assessments: the International Committee for the exploration of the Sea (ICES) and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). Following international standards for these type of documents allows environmental conditions and human impacts to be compared with similar studies in other marine regions around the world.

The organization of an assessment follows the sequence of physical oceanography, which defines the background conditions to which all organisms must adapt; biology, which reviews the living ecosystem properties and includes the exploitation of living resources from the sea; and chemistry, which governs the source and distribution of contaminants. Summary and overview chapters provide multidiscplinary synthesis, with particular emphasis on important issues related to anthropogenic modifications of the marine environment.

The first example of this type of assessment in Canada is "Marine Environmental Assessment of the Estuary and Gulf of St.Lawrence." The sister study to the Gulf assessment, "Marine Environmental Assessment of the Scotian Shelf and Inshore Areas," is in preparation.

Pelagic-Benthic Coupling in the Bay of Fundy

D.J.Wildish
Dept.Fisheries&Oceans,Biological Station,
St. Andrews, N.B. EOG2XO, Canada
506-529-8854 wildish@wolves.sta.dfo.ca

B.T.Hargrave, K.Kranck, T.G Milligan
Dept. Fisheries & Oceans, Bedford Institute of Oceanography, Dartmouth, N.S., B2Y4A2, Canada

Major primary production within the Bay of Fundy is by phytoplankton,whilst a large part of the secondary benthic production is from suspension-feeding horse mussels, *Modiolus modiolus*. The mussel reefs are extensive and occur intertidally to >100m depths. They comprise over 80% of all the secondary benthic production throughout the Bay.

We examine the distribution of particulate chlorophyll a (Chla) in the Bay as an indicator of living phytoplankton. Three zones are present determined by the degree of turbulent tidal mixing: stratified at the mouth in depths >100m and with Chla limited to the upper 20-40m, transitional in the mid-Bay at<100m and with Chla reaching to the bottom, well-mixed in the upper Bay at <80m and with Chla well-mixed from top to bottom. The major horse mussel reefs occur only on substrates where transitional and well-mixed seawater is present. This is consistent with the mussel reefs being trophically dependant on tidally transported, living phytoplankton.

The Chla concentration within the water column of the transitional zone is more than twice that in adjacent shallower or deeper areas. Multiple hypotheses are proposed to explain this:

1. turbulent tidal transport of phytoplankton into the transitional zone occurs from contiguos areas.
2. rapid turbulent tidal transport of live phytoplankton cells throughout the water column allows opportunities for carbon fixation by repeated transport into the euphotic layer.
3. flocculated particles within the transitional zone provides high particle fluxes to horse mussel beds during slack tide,because of the increased settling velocity of flocs.

Further research is required to determine the relative importance of these mechanisms.

(Key Words: Bay of Fundy, phytoplankton, macrobenthos, ecosystem analysis).

The Adjustment of Currents at the Shelf Break to a Channel Embedded in the Shelf/Slope Topography, with Application to the Northeast Channel

William J. Williams
MIT/WHOI Joint Program in Oceanography,
Woods Hole, MA 02543; USA
508-289-2803 williams@nereus.whoi.edu)

Glen G. Gawarkiewicz
WHOI, Woods Hole, MA 02543; USA
508-289-2913 glen@paddle.whoi.edu

Robert C. Beardsley
WHOI, Woods Hole, MA 02543; USA
508-289-2536 rbeardsley@whoi.edu

The episodic occurrence of Scotian Shelf water on the southern flank of Georges Bank during late-winter/early-spring is modeled numerically using a three dimensional primitive equation model. The modeling is oriented towards identifying the processes which allow the Scotian Shelf water to break the topographic constraint provided by the Northeast Channel and cross from the Scotian Shelf to Georges Bank.

The mean flow near the shelf-break over the southern Scotian Shelf flows south towards the Northeast Channel and then turns right and flows into the Gulf of Maine. As a simple attempt at modeling this flow, the adjustment of a barotropic jet near the shelf break to a channel embedded in the shelf/slope topography is studied. When the topography of the channel is strong, the flow turns on reaching the channel and flows along the edge of the channel. When the topography is weak, the flow crosses the channel.

For a channel with a v-shaped cross-section, there are three relevant non-dimensional parameters that govern the flow. These are the Rossby number of the shelf break jet U/fL, the Rossby number of the flow due to the channel width U/fD and the ratio of the depth of the shelf to the depth of the channel $h1/h2$, where U is the maximum speed of the inflow jet, L the half width of the inflow jet, f the Coriolis parameter, D the half width of the channel, $h1$ the depth of the shelf, and $h2$ the depth of the channel. Scalings are presented for the distance along the channel where the flow crosses, the radius of curvature of the flow in the channel, and the speed of the flow in the channel. These scalings are then extended to include channels with u-shaped cross-

sections, and inflow jets with varying positions relative to the shelf break.

(Key Words: Northeast Channel, Scotian Shelf water, numerical modeling, potential vorticity)

Numerical Simulations of the Gulf of Maine Seasonal Circulations Using the Princeton Ocean Model

Huijie Xue
University of Maine, Department of Oceanography,
5741 Libby Hall, Orono, ME 04469-5741
207-581-4318 hjx@athena.umeoce.maine.edu

Fei Chai, Neal Pettigrew
University of Maine, 5741 Libby Hall,
Orono, ME 04469-5741

The three dimensional nonlinear prognostic Princeton Ocean Model is applied to the Gulf of Maine. The model is initialized with climatological annual mean conditions and forced at the open boundaries with the monthly temperature and salinity distributions produced by the NOAA East Coast Forecast System (Aikman et al., 1995). A regular annual cycle is established after three years of integration. External forcings include momentum and buoyancy fluxes at the air-sea interface, inflows of Scotian Shelf Water and Slope Water, and river runoffs. This study tries to assess the importance of each forcing on the initiation and the progression of the annual cycle of the circulations in the Gulf of Maine.

(Key Words: Seasonal circulation, Gulf of Maine, numerical model).

Participants

Eric Adams
Massachusetts Institute of Technology
Department of Civil & Environmental Engineering
MIT Building 48-325
77 Massachusetts Avenue
Cambridge, MA 02139
617-253-6595
617-253-8850
eeadams@mit.edu

Robin Alden
Maine Department of Marine Resources
21 State House Station
Augusta, Maine 04333-0021
207-624-6553
207-624-6024
Robin.Alden@state.me.us

John H. Allen
Huntsman Marine Science Centre
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-1200
506-529-1212
allenj@nbnet.nb.ca

Ted Ames
P.O. Box 188
Stonington, ME 04681
207-367-5907
207-367-2829

John Anderson
Atlantic Salmon Federation
PO Box 429
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-1023
506-529-4985
atlsal@nbnet.nb.ca

Joseph Arbour
Environment Canada
15th Floor, Queen Square
45 Alderney Drive
Dartmouth, Nova Scotia B2Y 2N6 Canada
902-426-1701
902-426-8373
arbourj@ns.doe.ca

William Ayer
Department of Environment
P.O. Box 6000
361 Argyle Street
Fredericton, New Brunswick E3B 1T9 Canada
506-457-4846
506-457-7823
bayer@gov.nb.ca

Johann Baretta
Danish Hydraulics Institute
Ecological Modelling Centre
Agern Alle 5
DK-2970 Horsholm Denmark
+45 45 76 95 55
+45 45 76 25 67
job@sun20.dhi.dk

Hanneke Baretta-Bekker
Danish Hydraulics Institute
Ecosystem Modeling Centre
Agern Alle 5
DK-2970 Horsholm Denmark
+45 45 76 95 55
+45 45 76 25 67
hbb@vki.dk

Participants

Seth Barker
Maine Department of Marine Resources
Marine Sciences Laboratory
P.O. Box 8
West Boothbay Harbor, ME 04575-0008
207-633-9307
—
mrsbark@state.me.us

Walter Barnhardt
University of Maine
Department of Geological Sciences
Boardman Hall
Orono ME 04469
207-581-2202
207-581-2155
walterb@raven.spatial.maine.edu

David Bartlett
University of New Hampshire
Institute for the Study of Earth, Oceans and Space
Morse Hall
Durham, NH 03824
603-862-0322
603-862-1915
dbartlet@bigred.sr.unh.edu

Robert C. Beardsley
Woods Hole Oceanographic Institution
Department of Physical Oceanography
Clark 343B
360 Woods Hole Rd., MS #21
Woods Hole, Ma 02543-1541
508-289-2536
508-457-2181
rbeardsley@whoi.edu

Claudia Benitez-Nelson
Woods Hole Oceanographic Institution
Marine Chemistry and Geochemistry
266 Woods Hole Road
Woods Hole, MA 02543
508-289-2924
508-457-2193
claudia@athena.mit.edu

Heather Benway
University of New Hampshire
Morse 351
Institute for the Study of Earth, Oceans and Space
Durham, NH 03824
603-862-1542
603-862-1915
hmbenway@christa.unh.edu

Michael Bothner
U.S. Geological Survey
384 Woods Hole Road
Quisett Campus
Woods Hole MA 02543
508-457-2240
—
mbothner@nobska.usgs.er.gov

Robert Boudrow
University of New Hampshire
Morse 351
Institute for the Study of Earth, Oceans and Space
Durham, NH 03824
603-862-2477
603-862-1915
robert.boudrow@unh.edu

Bruce Bourque
Bates College
Anthropology Department
Lewiston, ME 04240
207-786-6080
207-786-6123
bbourque@abacus.bates.edu

Eugenia Braasch
Regional Association for Research on the Gulf of Maine
Dartmouth College
Thayer School of Engineering
Hanover, NH 03755-8000
603-646-3480
603-646-3856
braasch@dartmouth.edu

Margaret Brady
Massachusetts Coastal Zone Management Program
100 Cambridge Street, Room 2000
Boston, MA 02202
617-727-9530
617-727-2754
pbrady@state.ma.us

Jean Brochi
U.S. Environmental Protection Agency
Region I
JFK Federal Building
Boston, MA 02203
617-565-3582
—
brochi.jean@epamail.gov

David Brooks
Texas A & M University
Department of Oceanography
College Station, TX 77840
409-845-5527
409-845-6331
dbrooks@cobscook.tamu.edu

Wendell Brown
University of New Hampshire
Ocean Process Analysis Laboratory
Morse Hall
Durham, NH 03824
603-862-3153
603-862-0243
wsbrown@kelvin.unh.edu

Joseph Brown
Memorial University of Newfoundland
Ocean Science Centre
Marine Sciences Research Laboratory
St. John's, Newfoundland A1C 5S7 Canada
709-737-3252
709-737-3220
jabrown@morgan.ucs.mun.ca

Frank Bub
University of New Hampshire
Ocean Process Analysis Laboratory
Morse Hall
Durham, NH 03824-3525
603-862-3154
603-862-0243
frankb@kelvin.unh.edu

Marilyn Buchholtz ten Brink
U.S. Geological Survey
384 Woods Hole Road
Quisett Campus
Woods Hole, MA 02543
508-457-2392
508-457-2310
mtenbrin@nobska.er.usgs.gov

Robert Buchsbaum
Massachusetts Audubon Society
Endicott Regional Center
346 Grapevine Road
Wenham, MA 01984
508-927-1122
508-922-8487
rbuchsbaum@massaudubon.org

Les Burridge
Department of Fisheries and Oceans Canada
Biological Station
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-8854x.5903
506-529-5862
burridge@sta.dfo.ca

Michael Burt
Huntsman Marine Science Centre
Brandy Cove
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-1200
506-529-1212
huntsman@nbnet.nb.ca

Donna Busch
National Marine Fisheries Service
28 Tarzwell Drive
Narragansett, RI 02882
401-782-3270
401-782-3201
dbusch@fish1.gso.uri.edu

Bradford Butman
U.S. Geological Survey
Woods Hole Field Center
384 Woods Hole Road
Woods Hole, MA 02543-1598
508-457-2212
508-457-2309
bbutman@usgs.gov

Maria-Ines Buzeta
Department of Fisheries and Oceans Canada
Biological Station
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-8854 x.5904
506-529-5862

Janet Campbell
University of New Hampshire
Ocean Process Analysis Laboratory
140 Morse Hall
Durham NH 03824
603-862-1070
603-862-0243
campbell@kelvin.sr.unh.edu

Daniel Campbell
U.S. Environmental Protection Agency
Atlantic Ecology Division
27 Tarzwell Drive
Narrangansett RI 02882
401-782-3195
401-782-3030
campbell.dan@epamail.epa.gov

Maria Casas
University of Rhode Island
Graduate School of Oceanography
South Ferry Road
Narragansett, RI 02882
401-874-6581
401-874-6240
mcasas@gsosun1.gso.uri.edu

Fei Chai
University of Maine
Oceanography Department
5741 Libby Hall
Orono ME 04469-5741
207-581-4317
207-581-4388
fchai@athena.umeoce.maine.edu

Mark Chandler
New England Aquarium
Central Wharf
Boston, MA 02110-3399
617-973-0274
617-723-6207
mwc@neaq.org

Participants

Blythe Chang
Department of Fisheries and Oceans Canada
Director's Office
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-8854 x.5907
506-529-5862
chang@wolves.sta.dfo.ca

Matthew Charette
University of Rhode Island
Graduate School of Oceanography
Narragansett Bay Campus
South Ferry Road Box 200
Narragansett, RI 02882-1197
401-874-6273
401-874-6811
charette@gsosun1.gso.uri.edu

Margo Chase
University of New Hampshire
Jackson Estuarine Laboratory
Durham, NH 03824
603-862-2175
603-862-1101
mechase@hopper.unh.edu

Robert Chen
University of Massachusetts at Boston
Environmental Sciences Program
100 Morrissey Blvd
Boston, MA 02125-3393
617-287-7491
617-287-7474
chenr@umbsky.cc.umb.edu

Gail Chmura
McGill University
Dept.of Geography and Centre for Climate and Global Change Research
805 Sherbrooke Street W.
Montreal, Quebec, H3A 2K6 Canada
514-398-4111
514-398-7437
chmura@felix.geog.mcgill.ca

James Churchill
Woods Hole Oceanographic Institution
Clark 354, MS #21
Woods Hole, MA 02543-1541
508-289-2807
508-457-2181
jchurchill@whoi.edu

Philip Colarusso
U.S. Environmental Protection Agency
Water Quality Unit
Region I
JFK Federal Bldg.
Boston, MA 02203
617-565-3533
617-565-4940
colarusso.phil@epamail.epa.gov

Catherine Coniaris
University of New Hampshire
Morse 351
Institute for the Study of Earth, Oceans and Space
Durham, NH 03824
603-862-1542
603-862-1915
coniaris@christa.unh.edu

Philip Conkling
The Island Institute
410 Main Street
Rockland, ME 04841
207-594-9209
207-594-9314
pconkling@islandinstitute.org

Michael Connor
Massachusetts Water Resources Authority
Environmental Quality Department
100 First Avenue
Boston, MA 02129
617-241-6507
617-241-6526
enquad@world.std.com

David Coon
Conservation Council of New Brunswick
180 St. John Street
Fredericton, New Brunswick E3B 4A9 Canada
506-466-4033
506-466-2911
ccnbcoon@nbnet.nb.ca

Chris Cornelisen
Office of Massachusetts Coastal Zone Management
Massachusetts Executive Office of Environmental Affairs
100 Cambridge Street, Room 2000
Boston, MA 02202
617-727-9530
—
ccorneli@winnie.fit.edu

Robert Crawford
Nova Scotia Department of Fisheries
P.O. Box 2223
5151 George St., 7th Floor
Halifax, Nova Scotia B3J 3C4 Canada
902-424-0351
902-424-4671
fish.crawford@gov.ns.ca

Elizabeth Della Valle
Maine State Planning Office
38 State House Station
Agusta, ME 04333
207-287-2851
207-7287-6484
beth.DELLA.valle@state.me.us

Catherine Demos
U.S. Army Corps of Engineers
Environmental Branch - New England Division
424 Trapelo Road
Waltham, MA 02254-9149
617-647-8231
617-647-8560
catherine.j.demos@usace.army.mil

Scott Dickerson
The Island Institute
410 Main Street
Rockland, ME 04841
207-594-9209
207-594-9314
scottd@islandinstitute.org

Stephen Dickson
Maine Geological Survey
Natural Resources Information and Mapping Center
Department of Conservation 22 State House Station
Augusta, ME 04333-0022
207-287-7174
207-287-2353
stephen.m.dickson@state.me.us

Brian Doyle
University of New Hampshire
Kingman Farm
Durham, NH 03824-3512
603-749-1565
603-749-3997
brian.doyle@unh.edu

Edward Durbin
University of Rhode Island
Graduate School of Oceanography
South Ferry Road
Narragansett, RI 02882
401-874-6850
401-874-6240
edurbin@gsosun1.gso.uri.edu

Peter Eaton
Environment Canada
45 Alderny Drive
Dartmouth, Nova Scotia B2Y 2N6 Canada
902-426-4491
902-426-8373
peter.eaton@ec.gc.ca

James Elliott
Department of Fisheries and Oceans Canada
Ocean Sciences Division
Bedford Institute of Oceanography
P.O. Box 1006 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2 Canada
—

Alison Evans
Department of Fisheries and Oceans Canada
General Delivery Centre
Burlington, Nova Scotia B0N 1E0 Canada
902-426-8216
902-426-1489
nstn2910@fox.nstn.ca

Marie Evans
University of New Hampshire
The Institute for the Study of Earth, Oceans, and Space
Department of Earth Sciences
Morse Hall, 39 College Road
Durham, NH 03824-3525
—

Gordon Fader
Geological Survey of Canada
Bedford Institute of Oceanography
Box 1006
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-455-6100
902-426-4104
fader@agcrr.bio.ns.ca

John Farrington
Woods Hole Oceanographic Institution
360 Woods Hole Rd., MS#31
Woods Hole, MA 02543-1541
508-289-2200
508-457-2188
jfarrington@whoi.edu

George Finney
Environment Canada
P.O. Box 1590
63 East Main Street
Sackville, New Brunswick E0A 3C0 Canada
506-364-5011
506-364-5062
finneyg@ns.doe.ca

Derek Fong
Woods Hole Oceanographic Institution
Clark Laboratory 317, MS 21
MIT/WHOI Joint Program in Oceanography
Woods Hole, MA 02543-1541
508-289-2814
508-457-2181
thewho@fog.whoi.edu

Tim Ford
Harvard University
Harvard School of Public Health
665 Huntington Avenue
Boston, MA 02144
617-432-3434
617-432-3349
ford@endor.harvard.edu

Paul Fucile
Woods Hole Oceanographic Institution
Department of Physical Oeanography
Clark South, Woods Hole Road
Woods Hole, MA 02543
508-548-1400 ext.2622
508-457-2165
pfucile@whoi.edu

Participants

George Gardner
University of Massachusetts at Boston
Environmental Sciences Program
100 Morrissey Blvd.
Boston, MA 02125
617-287-7454
617-287-7474
gardner@umbsky.cc.umb.edu

Karen Garrison
University of New Hampshire
Ocean Process Analysis Lab
Morse Hall
Durham, NH 03824-3525
603-862-3156
603-862-0243
kmg@kepler.unh.edu

Wendy Gentleman
Dartmouth College
Thayer School of Engineering
Hanover, NH 03755
603-646-2685
603-646-3856
wendy.gentleman@dartmouth.edu

W. Rockwell Geyer
Woods Hole Oceanographic Institution
Department of Applied Physics and Ocean Engineering
Bigelow 98 Water Street, MS #12
Woods Hole, MA 02543-1053
508-289-2868
508-457-2194
rgeyer@whoi.edu

Gregory Gillis
Washburn & Gillis Associates Ltd.
25 Waggoners Lane
Fredericton, New Brunswick E3B 2L2 Canada
506-458-1000
506-450-0829
wgafton@nbnet.nb.ca

Donald Gordon
Department of Fisheries and Oceans Canada
Bedford Institute of Oceanography
Marine Environmental Sciences Division
P.O. Box 1006 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-3278
902-426-2256
gordond@mar.dfo-mpo.gc.ca

Lisa Graziano
Bigelow Laboratory for Ocean Sciences
P.O. Box 475
McKown Point Road
West Boothbay Harbor, ME 04575-0475
207-633-9600
207-633-9641
lgraziano@bigelow.org

John Green
National Marine Fisheries Service
28 Tarzwell Drive
Narragansett, RI 02882
401-782-3240
401-782-3201
jgreen@fish1.gso.uri.edu

David A. Greenberg
Department of Fisheries and Oceans Canada
Ocean Sciences Division
Bedford Institute of Oceanography
Coastal Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-2431
902-426-7827
d_greenberg@bionet.bio.dfo.ca

Charles Hannah
Oceadyne Environmental Consultants
373 Ridgevale Drive
Bedford, Nova Scotia B4A 3M2 Canada
902-835-6235
902-835-5205
channah@emerald.bio.dfo.ca

Gareth Harding
Department of Fisheries and Oceans Canada
Bedford Institute of Oceanography
Habitat Ecology Section
PO Box 1006 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-2672
902-426-2256
gareth.harding@maritimes.dfo.ca

Larry Harris
University of New Hampshire
Department of Zoology
Spaulding Life Science
Durham NH 03824
603-862-3897
603-862-3784
lharris@christa.unh.edu

Glen Harrison
Department of Fisheries and Oceans Canada
Ocean Sciences Division
Bedford Institute of Oceanography
P.O. Box 1006 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-3879
902-426-9388
g_harrison@bionet.bio.dfo.ca

Kats Haya
Department of Fisheries and Oceans Canada
Organic Contaminants Section
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-5916
506-529-5862
haya@sta.dfo.ca

Mary Hayes
Maine State Planning Office
Station #38, 184 State St.
Augusta, ME 04333
207-287-8940
207-287-8059
mary.hayes@state.me.us

Erica Head
Department of Fisheries and Oceans Canada
Ocean Sciences Division
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B27 4A2 Canada
902-426-2317
902-426-9388
erica.head@maritimes.dfo.ca

Barbara Healy
University of Massachusetts at Boston
Environmental Sciences Program
100 Morrissey Blvd.
Boston, MA 02125
617-287-7464
617-287-7474
G5578bheal@umbsky.cc.umb.edu

Peter Hennigar
Environment Canada
45 Alderney Drive
Dartmouth, Nova Scotia B2Y 2N6 Canada
902-426-6191
902-426-9709
hennigarp@atlantic.ns.doe.ca

Eileen Hofmann
Old Dominion University
Center for Coastal Physical Oceanography
Crittenton Hall
Norfolk, VA 23529
757-683-5334
757-683-5550
hofmann@ccpo.odu.edu

Monica Holboke
Dartmouth College
Thayer School of Engineering
Hanover, NH 03755
603-646-2685
603-646-3856
holboke@enki.dartmouth.edu

Susan Holtz
Stanbrae Road
Ferguson's Cove
Box 49, Site 15
RR 5 Armdale, Nova Scotia B31 4J5
Canada
902-477-3690
902-477-5464

Nick Houtman
University of Maine
Public Affairs Building
Orono, ME 04469-5761
207-581-3777
207-581-3776
nick_houtman@voyager.umeres.maine.edu

William Hubbard
U.S. Army Corps of Engineers
New England Division
424 Trapelo Road
Waltham, MA 02254-9149
617-647-8552
617-647-8560
William.A.Hubbard@ned01.usace.army.mil

Lewis Incze
Bigelow Laboratory for Ocean Sciences
P.O. Box 475 McKown Point
West Boothbay Harbor, ME 04575-0475
207-633-9600
207-633-9641
lincze@bigelow.org

Ken Jacobs
University of New Hampshire
OPAL/EOS
Durham, NH 03824
862-0195
—
jacobs@kelvin.sr.unh.edu

Norbert Jaworski
U.S. Environmental Protection Agency
202 Wordens Pond
Wakefield, RI 02879
401-782-3290
401-782-3201
jaworski@gsosun1.gso.uri.edu

Frank Johns
TAS Editorial Services
65 Deepwood Crescent
Halifax, Nova Scotia B3M 2Y5
Canada
902-443-6941
902-443-4949
tasjohns@fox.nstn.ca

Participants

Steve Jones
University of New Hampshire
Jackson Estuarine Laboratory
85 Adams Point Road
Durham, NH 03824-3427
603-862-2175
603-862-1101
shj@christa.unh.edu

Carolyn Jordan
University of New Hampshire
Complex Systems Research Center
Morse Hall
Durham, NH 03824
603-862-2927
603-862-0188
cjordan@kaos.sr.unh.edu

Irena Kaczmarska-Ehrman
Mount Allison University
Department of Biology
Sackville, New Brunswick E0A 3C0 Canada
506-364-2510
506-364-2505
iehrman@mta.ca

David H. Keeley
Maine State Planning Office
Station # 38 184 State Street
Augusta, ME 04333
207-287-1491
207-287-8059
david.keeley@state.me.us

Maureen Keller
Bigelow Laboratory for Ocean Sciences
P.O. Box 475
McKown Point Road
West Boothbay Harbor ME 04575-0475
207-633-9600
207-633-9641
mkeller@bigelow.org

Joseph T. Kelley
Maine Geological Survey
Department of Geological Sciences
5711 Boardman Hall
University of Maine
Orono, ME 04469-5711
207-581-2162
207-581-2202
jtkelley@maine.maine.edu

John R. Kelly
3 Willow Lane
Rye, NH 03870
603-430-8378
—
rkelly1776@aol.com

Mark Lazzari
Maine Department of Marine Resources
PO Box 8
West Boothbay Harbor ME 04575-0008
207-633-9569
207-633-9579
mrmlazz@state.me.us

David Libby
Maine Department of Marine Resources
Marine Resources Laboratory
P.O. Box 8
West Boothbay Harbor, ME 04575-0008
207-633-9500
207-633-9579
mrdlibb@state.me.us

Matthew Liebman
U.S. Environmental Protection Agency
Region 1
J.F.K. Federal Building (WQE)
Boston, MA 02203
617-565-4866
617-565-4940
bays@epamail.epa.gov

John Loch
Department of Fisheries and Oceans Canada
Maritimes Region
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-3492
902-426-8484
John.Loch@maritimes.dfo.ca

Theodore Loder
University of New Hampshire
The Institute for the Study of Earth, Oceans, and Space
Dept. of Earth Sciences
Morse Hall, 39 College Road
Durham, NH 03824-3525
603-862-3151
603-862-1915
ted.loder@unh.edu

Ronald Loucks
Loucks Oceanology Ltd.
24 Clayton Park Drive
Halifax, Nova Scotia B3M 1L3 Canada
902-443-1113
—
rloucks@atcon.com

R. Gregory Lough
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole Laboratory
166 Water Street
Woods Hole, MA 02543-1097
508-495-2290
508-495-2258
glough@whsun1.wh.whoi.edu

Daniel Lynch
Dartmouth College
Thayer School of Engineering
Hanover, NH 03755
603-646-2308
603-646-3856
daniel_r_lynch@dartmouth.edu

Cathy MacKenzie
Washburn & Gillis Associates Ltd.
25 Waggoners Lane
Fredericton, NB E3B 2L2
Canada
506-458-1000
506-450-0829
wgafton@nbnet.nb.ca

James Manning
National Marine Fisheries Service
166 Water Street
Woods Hole, MA 02543
508-495-2211
508-548-5124
jmanning@whsun1.wh.whoi.edu

Jennifer Martin
Department of Fisheries and Oceans Canada
Aquaculture Division
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-8854
506-529-5862
jlmartin@sta.dfo.ca

Caroline Martorano
University of New Hampshire
Morse 349
Biogeochemical Systems Center
39 College Road
Durham, NH 03824
603-862-4724
603-862-1915
cdm2@christa.unh.edu

Judith McDowell
Woods Hole Oceanographic Institution
Coastal Research Lab., # 209
193 Oyster Pond Rd., MS #2
Woods Hole, MA 02543-1525
508-289-2557
508-457-2172
jmcdowell@whoi.edu

Dennis McGillicuddy
Woods Hole Oceanographic Institution
Bigelow 209b MS11
Woods Hole, MA 02548
508-289-2683
dmcgillicuddy@whoi.edu

Dorothy Medeiros-Bergen
University of New Hampshire
Ocean Process Analysis Laboratory
Morse Hall
Durham, NH 03824
603-862-4397
—
dem@christa.unh.edu

Linda Mercer
Maine Department of Marine Resources
Marine Sciences Laboratory
P.O. Box 8
West Boothbay Harbor, ME 04575-0008
207-633-9525
207-633-9579
mrlmerc@state.me.us

Michael Moore
Woods Hole Oceanographic Institution
Biology Department
Redfield 2-46, MS #33
Woods Hole, MA 02543-0000
508-289-3228
508-457-2134
mmoore@whoi.edu

Bradley Moran
University of Rhode Island
Graduate School of Oceanography
South Ferry Road
Narragansett, RI 02882-1197
401-792-6531
401-792-6160
moran@gsosun1.gso.uri.edu

Byard Mosher
University of New Hampshire
Complex Systems Research Center
Institute for the Study of Earth, Oceans and Space
Morse Hall 39 College Road
Durham, NH 03824
603-862-4520
603-862-0188
byard@kaos.sr.unh.edu

Laura Mucklow
Cantox Inc.
5475 Spring Garden Road, Suite 603
Halifax, NS B3J 3T2 Canada
902-429-0278
902-429-0279
cantoxns@ra.isisnet.com

Christopher Naimie
Dartmouth College
Thayer School of Engineering
8000 Cummings Hall
Hanover, NH 03755
603-646-2119
603-646-3856
christopher.e.naimie@dartmouth.edu

Participants

Gilles Olivier
Department of Fisheries and Oceans Canada
Halifax Fisheries Research Laboratory
902-426-7588
902-426-1862
g_olivier@bionet.bio.dfo.ca

Fred Page
Department of Fisheries and Oceans Canada
Fisheries Oceanography
St. Andrews Biological Station
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-8854 x.5927
506-529-4274
f_page@bionet.bio.dfo.ca

Peter Partington
Department of Fisheries and Oceans Canada
Scotia Fundy Fisheries Maritimes Region
P.O. Box 550
Halifax, Nova Scotia B3J 2S7 Canada
902-426-2583
902-426-7967
pat.young@sfnet.dfo.ca

John Pearce
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole Laboratory
166 Water Street
Woods Hole, MA 02543
508-495-2261
—
jack.pearce@noaa.gov

Judith Pederson
Massachusetts Institute of Technology
MIT Sea Grant Program
77 Massachusetts Ave. E38-300
Cambridge, MA 02139
617-252-1741
617-252-1615
jpederso@mit.edu

Richard Peterson
Department of Fisheries and Oceans Canada
Finfish Aquaculture Section
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-5929
506-529-5862

Neal Pettigrew
University of Maine
Department of Oceanography
218 Libby Hall
Orono, ME 04469-5741
207-581-4384
207-581-4388
nealp@maine.maine.edu

Steven Pike
University of Rhode Island
Graduate School of Oceanography
South Ferry Road
Narragansett, RI 02882-1197
401-874-6259
401-874-6811
spike@gsosun1.gso.uri.edu

Wilfred Pilgrim
New Brunswick Department of Environment
Air Quality Section
P.O. Box 6000
364 Argyle Street
Fredericton, NB E3B 5H1 Canada
506-453-3624
506-453-2265
wilfp@gov.nb.ca

Vicki Pilon
University of New Hampshire
Morse 351
Institute for the Study of Earth, Oceans and Space
Durham, NH 03824
603-862-1542
603-862-1915

Cynthia Pilskaln
University of Maine
Department of Oceanography
5741 Libby Hall
Orono, ME 04469-5741
207-581-4364
207-581-4388
pilskaln@maine.maine.edu

Gerhard Pohle
Huntsman Marine Science Centre
Atlantic Reference Centre
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-1203
506-529-1212
arc@sta.dfo.ca

Jeffrey Proehl
Dartmouth College
Thayer School of Engineering
8000 Cummings Hall
Hanover, NH 03755
603-646-3803
603-646-2277
jeff.proehl@dartmouth.edu

Jon Rittgers
National Marine Fisheries Service
1 Blackburn Drive
Gloucester, MA 01930-2298
508-281-9311
508-281-9371
j.rittgers@noaa.gov

Shawn Robinson
Department of Fisheries and Oceans Canada
Invertebrate Fisheries Section
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-5932
506-529-5862

Elva Romanow
University of Massachusetts at Boston
Environmental Sciences Program
100 Morrissey Blvd.
Boston, MA 02125
617-287-7464
617-891-2838
ewohlers@bentley.edu

Rodney Rountree
National Marine Fisheries Service
Northeast Fisheries Science Center
166 Water Street
Woods Hole, MA 02543
508-495-2340
508-495-2258
rrountre@whsun1.wh.whoi.edu

Steven Rudnick
University of Massachusetts at Boston
Environmental Sciences Program S/1/058
100 Morrissey Blvd.
Boston, MA 02125-3393
617-287-7448
617-287-7474
7001srudn@umbsky.cc.umb.edu

Bob Rutherford
Department of Fisheries and Oceans Canada
Maritimes Region
PO Box 550
Halifax, Nova Scotia B3J 2S7 Canada
902-426-8398
902-426-3479
bob.rutherford@maritimes.dfo.ca

Daniel Schick
Maine Department of Marine Resources
Marine Resources Laboratory
P.O. Box 8
West Boothbay Harbor, ME 04575
207-633-9528
207-633-9579
mrdschi@state.me.us

Ronald Schlitz
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole Laboratory
166 Water Street
Woods Hole, MA 02543-1097
508-495-2395
508-495-2258
rschlitz@whsun1.wh.whoi.edu

Jerry Schubel
New England Aquarium
Central Wharf
Boston, MA 02110-3399
617-973-5220
617-973-0276
jschubel@neaq.org

Jack Schwartz
Division of Marine Fisheries
Cat Cove Marine Lab.
92 Fort Ave.
Salem, MA 01970
508-745-3107 x.122
617-727-1306 x.142
jschwartz@state.ma.us

Nancy Shackell
Dalhousie University
6563 Berlin Street
Halifax, Nova Scotia B3L 1T8 Canada
902-455-5486
–
shackell@phys.ocean.dal.ca

Glyn Sharp
Department of Fisheries and Oceans Canada
Fisheries Research Lab
1707 Water Street PO Box 550
Halifax, Nova Scotia B3J 2S7 Canada
902-426-6042
902-426-1862
g_sharp@bionet.dfo.ca

James Shine
Harvard University
School of Public Health Dept. of Environmental Health
Building I Room G19
665 Huntington Avenue
Boston, MA 02115
617-432-0272
617-432-3349
jshine@hsph.harvard.edu

Bruce Sidell
University of Maine
School of Marine Sciences
218 Libby Hall
Orono, ME 04469
207-581-4381
207-581-4388
bsidell@maine.maine.edu

Richard Signell
U.S. Geological Survey
384 Woods Hole Road
Quisett Campus
Woods Hole, MA 02543
508-457-2229
508-457-2310
rsignell@usgs.gov

Participants

William Silvert
Department of Fisheries and Oceans Canada
Habitat Ecology Section
Bedford Institute of Oceanography
PO Box 1006
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-1577
902-426-7827
silvert@scotia.dfo.ca

Chris Simmers
State of NH Dept.of Environmental Services
6 Hazen Drive
Concord, NH 03301
603-271-2961
603-271-2867
simmers@desplan.mv.com

Michael Sinclair
Department of Fisheries and Oceans Canada
Marine Fish Division
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-3130
902-426-7827
m_sinclair@bionet.bio.dfo.ca

Peter Smith
Department of Fisheries and Oceans Canada
Bedford Institute of Oceanography
Coastal Ocean Science, Ocean Science Division
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-3474
902-426-7827
pc_smith@bionet.bio.dfo.ca

Susan Snow-Cotter
Office of Massachusetts Coastal Zone Management
Massachusetts Executive Office of Environmental Affairs
100 Cambridge Street, Room 2000
Boston, MA 02202
617-727-9530 x.210
617-727-2754
ssnow-cotter@state.ma.us

John Sowles
Maine Department of Environmental Protection
State House Station #17
Augusta, ME 04333
207-287-6110
207-287-7191
john.sowles@state.me.us

Robert Steneck
University of Maine
Darling Marine Center
25 Clark's Cove Road
Walpole, ME 04573
207-563-3146 x.233
—
steneck@maine.maine.edu

David Stevenson
Maine Department of Marine Resources
Marine Sciences Laboratory
P.O. Box 8
West Boothbay Harbor, ME 04575-0008
207-633-9530
207-633-9579
mrdstev@state.me.us

Marie Studer
Massachusetts Bays Program
100 Cambridge St., 20th Floor
Boston, MA 02202
617-727-9530 x405
617-727-7235
mstuder@state.ma.us

Darrell Taylor
Nova Scotia Department of the Environment
PO Box 2107
Terminal Road
Halifax Nova Scotia B3J 3B7 Canada
902-424-2570
902-424-0503
hlfxterm.envi.taylordl@gov.ns.ca

Laura Taylor
Maine State Planning Office
Maine Coastal Program
Station #38
Augusta, ME 04333
207-287-8790
207-287-8059
laura.taylor@state.me.us

Richard Taylor
Gloucester Aquaculture Project
Box 7002
Gloucester, MA 01930
508-281-3146
—
rtaylor@cove.com

Andrew Thomas
University of Maine
School of Marine Sciences
Orono, ME 04469
207-581-4335
207-581-4388
thomas@maine.maine.edu

Gordon Tidmarsh
Texaco Canada Petroleum Inc.
3100 150 6th Ave. SW
Calgary, Alberta T2V 2NH Canada
403-234-2935
403-234-2999

David Townsend
University of Maine
Department of Oceanography
5741 Libby Hall
Orono, ME 04469-5741
207-581-4367
207-581-4388
davidt@maine.maine.edu

Deborah Trefts
Yale University/Dalhousie University
2051 Beech Street
Halifax, Nova Scotia B3L 2X7 Canada
902-494-1102
902-494-1316
dtrefts@kilcom1.ucis.dal.ca

Bruce Tripp
Woods Hole Oceanographic Institution
Rinehart Coastal Research Center
193 Oyster Pond Road, MS #2
Woods Hole, MA 02543-1525
508-289-2900
508-457-2172
btripp@whoi.edu

Megan Tyrrell
University of New Hampshire
Zoology Department
Biologial Sciences Building
Durham, NH 03824
—

Raul Ugarte
Acadian Seaplants Limited
P.O. Box 90
Pennfield, New Brunswick Canada
902-468-2840
506-849-2773
rugarte@atcon.com

Page Valentine
U.S. Geological Survey
Quisett Campus
384 Woods Hole Road
Woods Hole, MA 02543
508-457-2239
508-457-2310
pvalentine@usgs.gov

Lou Van Eeckhaute
Department of Fisheries and Oceans Canada
Gulf of Maine Section
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-5938
506-529-5862

Lou Van Guelpen
Huntsman Marine Science Centre
Atlantic Reference Centre
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-1203
506-529-1212
arc@sta.dfo.ca

Penny Vlahos
University of Massachusetts at Boston
Environmental Sciences Program
100 Morrissey Blvd.
Boston, MA 02125
617-287-7448
617-287-7474
G5128evlah@umbsky.cc.umb.edu

Susan Waddy
Department of Fisheries and Oceans Canada
Invertebrate Fisheries Section
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-5890
506-529-5862
s_waddy@bionet.bio.dfo.ca

Brenda Waiwood
Department of Fisheries and Oceans Canada
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-5866
506-529-5862
bwaiwood@sta.dfo.ca

Ken Waiwood
Department of Fisheries and Oceans Canada
Organic Contaminants Section
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-5973
506-529-5862

Robert Wall
University of Maine
Center for Marine Studies
5715 Coburn Hall, Room 14
Orono, Maine 04469-5715
207-581-1435
207-581-1426
robert_wall@voyager.umeres.maine.edu

Gordon Wallace
University of Massachusetts at Boston
Environmental Coastal and Ocean Sciences Program
Boston Harbor Campus
100 Morrisey Blvd.
Boston, MA 02125
617-287-7440
617-287-7474
wallace@umbsky.cc.umb.edu

Leslie Watling
University of Maine
Darling Marine Center
25 Clark's Cove Road
Walpole, ME 04573
207-563-3146 x. 4248
—
watling@maine.miane.edu

Wendy Watson-Wright
Department of Fisheries and Oceans Canada
St. Andrews Biological Station
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-8854
506-529-4274
w3@wolves.sta.dfo.ca

Peter Wells
Environment Canada
Environmental Conservation Branch
CWS, 5th floor Queen's Square
45 Alderney Drive
Dartmouth, Nova Scotia B2Y 2N6 Canada
902-426-1426
902-426-4457
pwells@is.dal.ca

Francisco Werner
University of North Carolina
12-7 Venable Hall, CB #3300
Marine Sciences Program
Chapel Hill, NC 27599-3300
919-962-0269
919-962-1254
cisco@marine.unc.edu

Sandra Werner
Woods Hole Oceanographic Institution
MIT/WHOI Joint Program in Oceanography
Physical Oceanography Department
Clark 358B, MS #21
Woods Hole, MA 02543-1541
508-289-2802
508-457-2181
sandra@sound.mit.edu

Louise White
Department of Fisheries and Oceans Canada
Marine Environmental Sciences Division
Bedford Institute of Oceanography
PO Box 1006
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-3658
902-426-6695
l_white@bionet.bio.dfo.ca

Fred Whoriskey
Atlantic Salmon Federation
P.O. Box 429
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-1039
506-529-4985
atlsal@nbnet.nb.ca

David Wildish
Department of Fisheries and Oceans Canada
Biological Sciences Branch
Scotia-Fundy Region
St. Andrews Biological Station
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-8854
506-529-5862
wildish@wolves.sta.dfo.ca

William Williams
Woods Hole Oceanographic Institution
MIT/WHOI Joint Program in Oceanography
Clark 340B, MS #21
Woods Hole, MA 02543-1541
508-289-2803
508-457-2181
williams@nereus.whoi.edu

Huijue Xue
University of Maine
Department of Oceanography
Room 206, 5741 Libby Hall
Orono, ME 04469-5741
207-581-4318
207-581-4388
hjx@athena.umeoce.maine.edu

Phil Yeats
Department of Fisheries and Oceans Canada
Marine Environmental Science Division
Bedford Institute of Oceanography
PO Box 1006
Dartmouth, Nova Scotia B2Y 4A2 Canada
902-426-7272
902-426-6695
p_yeats@bionet.bio.dfo.ca

Yi Xian Zhang
University of Massachusetts at Boston
100 Morrissey Blvd.
Boston, MA 02125
617-287-7461
—
G8828Y2HAN@umbsky.cc.umb.edu

Vlado Zitko
Department of Fisheries and Oceans Canada
Organic Contaminants Section
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
506-529-5942
506-529-5862
zitko@wolves.sta.dfo.ca

Mechanisms for Improving the Integration of Science and Management in Decisions Affecting the Environmental Quality of the Gulf of Maine

Workshop at Migis Lodge, Sebago Lake, Maine
June 2-3, 1997

RARGOM Report 97-2

The need to incorporate state-of-the-art science and management strategies in response to contemporary and emerging issues affecting the environmental quality of coastal ecosystems has been well-documented in a series of case studies and workshops. The Regional Association for Research on the Gulf of Maine (RARGOM) is convening a series of workshops which are intended to foster improved stewardship of environmental resources through an informed partnership of scientists, managers, the public, and non-governmental organizations as environmental policy is developed in the Gulf of Maine region (RARGOM Reports 96-1, 97-1). The series began with the "Gulf of Maine Ecosystem Dynamics Scientific Symposium and Workshop" held in St. Andrews, New Brunswick, Canada in September, 1996. This was primarily a scientific conference, but a highly visible and deliberate part of the program involved managers in the Gulf of Maine region who were invited to present regional environmental issues of concern requiring additional scientific knowledge for their solution. It was agreed at the conference that the knowledge sought by management often was of fundamental scientific interest as well. So, why isn't there a better working relationship between the two communities, one which presumably could benefit both? This became the subject of the second workshop and is the topic of this report.

This second workshop, held at Sebago Lake, Maine in June 1997, brought together a range of scientific and management expertise from the United States and Canada to assess improved mechanisms for effective interactions between the scientific and resource management communities in the Gulf of Maine. Participants were asked to help identify appropriate structures, functions, responsibilities and support needed to improve the integration of scientific and management expertise in the region on both sides of the international boundary. Workshop participants generally agreed with the broad recommendations and concepts contained in the recent National Research Council report entitled "Science, Policy and the Coast: Improving Decisionmaking" (1995). The current workshop was conducted specifically to involve regional managers and scientists who would make recommendations which they felt could be endorsed and used by their agencies and institutions to try to effect change.

While this second workshop emphasized the perceptions of scientists and managers, the need to involve the broader public sector in the solution of environmental problems was also recognized. RARGOM intends to focus on these additional interfaces between science, management, the public, and non-governmental organizations in future collaborative work.

This report is intended for the research and natural resources management communities. We challenge the reader to take personal responsibility for disseminating this document and promoting its recommendations within their sphere of responsibility. Institutional leaders, recognizing the importance of sound scientific information in effective policy making, should plan for and implement these recommendations by such measures as reallocating existing resources and identifying new resources for programs designed to improve information dissemination and utilization.

Three categories of recommendations resulted from this workshop: A). apply the region's expertise to current and emerging issues; B). improve regional information management and dissemination; C). develop new tools to integrate science and policy. These are outlined in more detail below.

A. Apply the Region's Expertise to Current and Emerging Issues

A broad, long-term vision for the Gulf of Maine ecosystem must be developed that can guide policy development, decision-making and research. This will facilitate flexible responses to current problems and better anticipation of emerging issues because it provides a cohesive framework about which focused agency-specific and time-specific needs can be identified and prioritized. The Gulf of Maine Council on the Marine Environment should bring stakeholders together over the next year to create a shared, long-term vision for the Gulf of Maine, providing a direction for the future, identifying information needs, and specifying a process for user involvement. Building a long-term vision requires a collaborative and mutually-rewarding partnership between scientists, managers, the public and non-governmental organizations. It is recommended that the management and research communities take the following steps to make this happen:

1. **Establish independent and credible scientific advisory groups to help identify emerging issues, to set priorities for research and to provide the best available advice on issues of immediate concern.** Advisory groups should consist of both long-term oversight committees and *ad hoc* expert panels, be financially supported, and responsive, but not captive, to management needs.
2. **Recognize the potential value of scientific contributions to societal needs and improve the mechanisms for applying this expertise.** The scientific reward systems (both academic and governmental) need to be addressed because they often fail to adequately recognize and reward professional time invested in public service. In addition to the generation of new knowledge, the integration, application and transmission of that knowledge must be considered valid activities of scholarship (Boyer, 1990). Administrators in both academic and government research organizations should convene groups of scientists to discuss necessary changes in reward systems so that scientific expertise is more readily available to meet management needs.
3. **Provide financial resources to enable scientists to participate in applied scholarship, technical advisory roles, and the identification of research needs that are important to resource managers.** Both the management and science communities benefit from these activities, and they should work together to expand support for these purposes.
4. **Develop programs that emphasize new skills and relationships required for integration of scientific and management activity.** University training programs are needed in such areas as adaptive management (National Research Council, 1995) and risk assessment. New students as well as mid-career scientists and managers should participate. Relationships built by frequent personal interaction help to establish better communication, trust, and understanding of scientific and technical approaches.

The relationships and training referred to in recommendation 4 require time and trade-offs on the part of managers and scientists. This is likely to happen only in an environment which promises some stability to the enterprise and its rewards. Thus, training (recommendation 4), culture change (recommendation 2) and financial resources (recommendation 3) are all important aspects to implementation.

An example of a visible and successful partnership between managers and scientists in the Gulf of Maine region is illustrated by the Massachusetts Water Resources Authority (MWRA) technical advisory committee. The committee, convened by the Secretary of Environmental Affairs of the Commonwealth of Massachusetts, has provided advice on a wide variety of MWRA activities (representing a four billion dollar investment over fifteen years). The committee goals are to enhance the environmental quality of Boston Harbor, while at the same time, to avoid significant compromise of the environmental quality of Massachusetts Bay. Projects include the design and siting of the outfall diffuser location in Massachusetts Bay and the design and implementation of its ongoing monitoring plan. The MWRA has been able to objectively address a number of critical uncertainties surrounding its projects through an effective third-party review process provided by the technical advisory committee. In general, the MWRA efforts have been well received by the public.

B. Improve Regional Information Management and Dissemination

A regionally-developed information management system is essential for improving communication between scientists and managers within and across political boundaries. Such a system should include scientific databases, synthesized data and selected information products for more general use. Scientists are using distributed databases routinely; these should be expanded to provide managers and policy makers with access to products that they need. The basis of resource management decisions should be summarized and fully documented in a form that is publicly available. Scientific input for decisions should be identified and made available to all interested parties on electronic networks and other information products.

Development of information management systems will require fiscal and human resources for maintenance, management, and quality control or assessment. Institutional leaders should provide the resources necessary to profile the scientific databases and make them accessible and useful to managers. In order to make information available in a format appropriate to managers and policy-makers, increased support is needed for well-trained personnel and soft/hardware capabilities that can synthesize and translate scientific information.
To accomplish this, it is recommended that:

1. **Managers document the basis for their decisions and summarize decision-making processes for the benefit of the public, the policy-making community and scientists.** Appropriate documentation is needed to learn how scientific information is ultimately used in the decision-making process.
2. **Scientists and managers recognize that successful communication is a two-way process.** An understanding of the time frames involved, so that appropriate lead time and timely feedback can be provided, is integral to such interactions.
3. **Public agencies and research organizations support scientists and managers who serve as synthesizers, translators, and communicators in the integration of science into management decisions and public policy.** The costs of providing scientific translation should be included in the research funding and/or be borne by the management agency needing the translation. Scientific translators and communicators should be supported to develop syntheses of data, deliver annual briefings, and provide documentation of how scientific information has been, is, or will be used to assist with decision-making. Scientific and technical information available for decision-making inevitably contains uncertainty for which scientists should prepare an understandable, non-technical explanation.
4. **Regional organizations establish, maintain and enhance the information infrastructure.** RARGOM and the Gulf of Maine Council on the Marine Environment should collaboratively assess EDIMS, REDIMS, and other regional information databases in both the United States and Canada, and ensure appropriate support for the continuing development of this infrastructure. Predictive modeling efforts that assist in the visualization of scientific data are necessary in order to better understand ecosystems and to improve the decision-making process.
   RARGOM and the Gulf of Maine Council on the Marine Environment should collaboratively develop the organizational capacity (electronic communication, networking, etc.) to serve as a clearing house of information by scientific advisors, translators, and managers.

C. Develop New Tools to Integrate Science and Policy

Integrating science into the decision-making process will be facilitated by the development of new tools that can be used interactively by both scientists and managers. Interactive tools need to account for the uncertainty existing in experimental data, models, environmental standards and policy formulation and decisions. Risks must be acknowledged in the decision-making process. It is recommended that scientists and managers in the region:

1. **Develop better procedures for risk assessment and estimates of uncertainty.** Managers should pose questions for the scientists in terms of probability of occurrence and probability for variation; the process should often include contingency plans and other strategies as well as resources for evaluating the impacts of decisions made, responding to uncertainty, and managing risks.
2. **Use adaptive management techniques, including research and monitoring programs, to evaluate the impacts of policy decisions, to test predictions of environmental impacts, and to provide timely communication of results to project management.**
3. **Systematically review environmental regulations to improve effectiveness and reduce procedural complexity.**
4. **Develop contingency plans to deal with major environmental disturbances such as coastal oil spills and hurricanes.**
5. **Improve anticipatory planning in both science and management activities.** RARGOM should organize periodic region-wide briefings on new scientific developments that are relevant to management and other users.
6. **Develop and apply an integrated ecosystem perspective in addressing environmental issues (e.g., on the scale of a watershed, estuary, coastal bay, etc.) that bear on the structure, functioning of the marine system and the societal stresses on it.**
7. **Strive to apply common tools and approaches consistently across political jurisdictions in both Canada and the United States in recognition of the cross-boundary character of the natural system under our collective stewardship.**

Acknowledgments

This workshop was supported by the Department of Fisheries and Oceans Canada, the Gulf of Maine Council on the Marine Environment with funds from the U.S. Environmental Protection Agency, the Gulf of Maine Regional Marine Research Program, the Maine Department of Marine Resources, the Maine State Planning Office/Coastal Program, the New Brunswick Department of Environment, and the New Brunswick Department of Fisheries and Aquaculture.

We wish to thank the three workshop co-chairs for their contributions on many levels; the collaboration of Steven Ballard, Michael Connor, and Donald Gordon brought key insights and expertise to this program. The workshop was conceived, initiated and organized through the efforts of the steering committee members: William Ayer, Leigh Bridges, Richard Delaney, William Hubbard, Lewis Incze, David Keeley, Linda Mercer, Judith Pederson, Jan Smith, Laura Taylor, David Townsend, Bruce Tripp, and Gordon Wallace. Plenary talks by Bradford Butman, Donald Gordon, Evan Richert, and Jerry Schubel brought regional perspectives from the vantage points of manager and scientist and challenged the participants of the workshop to think about new approaches to our shared stewardship of the Gulf of Maine. Working group facilitators John Allen, Michael Connor, Donald Gordon, Laura Taylor and Bruce Tripp ensured that the workshop recommendations were formed in the context of contemporary Gulf of Maine issues. We thank the Migis Lodge for exceptional hospitality in a fine setting, and we acknowledge the contributions of all meeting participants to this report. Comments and recommendations for future workshops on this topic (including the names of individuals and organizations who might be involved) can be addressed to Genie Braasch, RARGOM.

References

Boyer, E., 1990. Scholarship Reconsidered: Priorities of the Professorate. Princeton, NJ. The Carnegie Foundation.

Department of Fisheries and Oceans Canada. 1986. Policy for the management for Fish Habitat. Ottawa, Ontario: DFO 3524, October, 1986.

Gulf of Maine Ecosystem Dynamics: Scientific Symposium Report. 1997. RARGOM Report 97-1. G. Wallace and E. Braasch, eds.

National Research Council. 1995. Science, Policy and the Coast: Improving Decisionmaking. Washington, D.C., National Academy Press.

The Health of the Gulf of Maine Ecosystem: Cumulative Impacts of Multiple Stressors. 1996. RARGOM Report 96-1, D. Dow and E. Braasch, eds.

Participant List

David Aiken
Department of Fisheries and Oceans Canada
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
tel.: 506-529-8854 fax: 506-529-8244
aiken@sta.dfo.ca

John Allen
Huntsman Marine Science Centre
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
tel.: 506-529-1200 fax: 506-529-1212
allenj@nbnet.nb.ca

William Ayer
New Brunswick Department of Environment
P.O. Box 6000
361 Argyle Street
Fredericton, NB E3B 1T9 Canada
tel.: 506-457-4846 fax: 506-457-7823
bayer@gov.nb.ca

Ivar Babb
University of Connecticut at Avery Point
National Undersea Research Center
1084 Shennecossett Road
Groton, CT 06340
tel.: 860-405-9119 fax: 860-445-2969
babb@uconnvm.uconn.edu

Steven Ballard
University of Maine
5715 Coburn Hall
Orono, Maine 04469
tel.: 207-581-1645 fax: 207-581-1266
steve_ballard@voyager.umeres.maine.edu

Wayne Barchard
Environment Canada
5th Floor, 45 Aldernay Drive
Dartmouth, Nova Scotia B2Y 2N6 Canada
tel.: 902-426-4695 fax: 902-426-8373
wayne.barchard@ec.gc.ca

John Boreman
National Marine Fisheries Service
Northeast Fisheries Science Center
166 Water Street
Woods Hole, MA 02543
tel.: 508-495-2365 fax: 508-495-2232
John.Boreman@noaa.gov

Eugenia Braasch
Regional Association for Research on the Gulf of Maine
Dartmouth College
Thayer School of Engineering
Hanover, NH 03755-8000
tel.: 603-646-3480 fax: 603-646-3856
braasch@dartmouth.edu

Margaret Brady
Massachusetts Coastal Zone Management Program
100 Cambridge Street, Room 2000
Boston, MA 02202
tel.: 617-727-9530 fax: 617-727-2754
pbrady@state.ma.us

Leigh Bridges
Massachusetts Division of Marine Fisheries
100 Cambridge Street
Boston, MA 02202
tel.: 617-727-3196 fax: 617-727-7988
lbridges@state.ma.us

Wendell Brown
University of New Hampshire
Ocean Process Analysis Laboratory
Morse Hall
Durham, NH 03824
tel.: 603-862-3153 fax: 603-862-0243
wsbrown@kelvin.unh.edu

Bradford Butman
U.S. Geological Survey
Woods Hole Field Center
384 Woods Hole Road
Woods Hole, MA 02543-1598
tel.: 508-457-2212 fax: 508-457-2309
bbutman@usgs.gov

Blythe Chang
Department of Fisheries and Oceans Canada
DirectorÕs Office
St. Andrews Biological Station
Brandy Cove Road
St. Andrews, New Brunswick E0G 2X0 Canada
tel.: 506-529-8854 x.5907
fax: 506-529-5862
chang@wolves.sta.dfo.ca

Michael Connor
Massachusetts Water Resources Authority
Environmental Quality Department
100 First Avenue
Boston, MA 02129
tel.: 617-241-6507 fax: 617-241-6526
enquad@world.std.com

Jeremy Conway
Department of Fisheries and Oceans Canada
Marine Mammal and Plant Advisor
PO Box 550, Station M
Halifax, Nova Scotia B3J 2S7 Canada
tel.: 902-426-9609 fax: 902-426-9683

Robert Crawford
Nova Scotia Department of Fisheries
P.O. Box 2223
5151 George St., 7th Floor
Halifax, Nova Scotia B3J 3C4 Canada
tel.: 902-424-0351 fax: 902-424-4671
fish.crawford@gov.ns.ca

Richard Delaney
University of Massachusetts at Boston
100 Morrissey Blvd.
Boston, MA 02125-3393
tel.: 617-287-5570 fax: 617-287-5575
urbharbors@umbsky.cc.umb.edu

Elizabeth Della Valle
Maine State Planning Office
State House Station #38
August, ME 04333
tel.: 207-287-2851
beth.della.valle@state.me.us

Scott Dickerson
The Island Institute
410 Main Street
Rockland, ME 04841
tel.: 207-594-9209 fax: 207-594-9314
scottd@islandinstitute.org

Peter Eaton
Environment Canada
45 Alderny Drive
Dartmouth, Nova Scotia B2Y 2N6 Canada
tel.: 902-426-4491 fax: 902-426-8373

Donald Gordon
Department of Fisheries and Oceans Canada
Bedford Institute of Oceanography
Marine Environmental Sciences Division
P.O. Box 1006 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2 Canada
tel.: 902-426-3278 fax: 902-426-2256
gordond@mar.dfo-mpo.gc.ca

Nick Houtman
University of Maine
Public Affairs Building
Orono, ME 04469-5761
tel.: 207-581-3777 fax: 207-581-3776
nick_houtman@voyager.umeres.maine.edu

Lewis Incze
Bigelow Laboratory for Ocean Sciences
P.O. Box 475
McKown Point
West Boothbay Harbor, ME 04575-0475
tel.: 207-633-9600 fax: 207-633-9641
lincze@bigelow.org

Steve Jones
University of New Hampshire
Jackson Estuarine Laboratory
85 Adams Point Road
Durham, NH 03824-3427
tel.: 603-862-2175 fax: 603-862-1101
shj@christa.unh.edu

Francis Juanes
University of Massachusetts at Amherst
Department of Forestry & Wildlife Management
Holdsworth Hall Box 34210
Amherst, MA 01003-4210
tel.: 413-545-1770 fax: 413-545-4358
juanes@forwild.umass.edu

David Keeley
Maine State Planning Office
Station # 38 184 State Street
Augusta, ME 04333
tel.: 207-287-1491 fax: 207-287-8059
david.keeley@state.me.us

Christian Krahforst
Massachusetts Coastal Zone Management Program
100 Cambridge St.
Boston, MA 02022
tel.: 617-727-9530 ext.415
fax: 617-727-2754
ckrahforst@state.ma.us

Linda Mercer
Maine Department of Marine Resources
Marine Sciences Laboratory
P.O. Box 8
West Boothbay Harbor, ME 04575-0008
tel.: 207-633-9525 fax: 207-633-9579
mrlmerc@state.me.us

Judith Pederson
Massachusetts Institute of Technology
MIT Sea Grant Program
77 Massachusetts Ave. E38-300
Cambridge, MA 02139
tel.: 617-252-1741 fax: 617-252-1615
jpederso@mit.edu

Gerald Pesch
U.S. Environmental Protection Agency
Environmental Research Laboratory
27 Tarzwell Dr.
Narragansett, RI 02882
tel.: 401-782-3007 fax: 401-782-3099
pesch.gerald@epamail.epa.gov

Evan Richert
Maine State Planning Office
184 State Street
38 State House Station
Augusta, ME 04333
tel.: 207-287-3261 fax: 207-287-6489
evan.d.richert@state.me.us

Jerry Schubel
New England Aquarium
Central Wharf
Boston, MA 02110-3399
tel.: 617-973-5220 fax: 617-973-0276
jschubel@neaq.org

Jan Smith
Massachusetts Coastal Zone Management Program
100 Cambridge St., Room 2000
Boston, MA 02202
tel.: 617-727-9530 x.419
fax: 617-727-2754
jsmith_eoea@state.ma.us

David Stevenson
Maine Department of Marine Resources
Marine Sciences Laboratory
P.O. Box 8
West Boothbay Harbor, ME 04575-0008
tel.: 207-633-9530 fax: 207-633-9579
mrdstev@state.me.us

Laura Taylor
Maine State Planning Office
Maine Coastal Program
Station #38
Augusta, ME 04333
tel.: 207-287-8790 fax: 207-287-8059
laura.taylor@state.me.us

Brian Thompson
Department of Fisheries and Oceans Canada
17th Floor, North Wing
1505 Barrington Street P.O Box 550
Halifax, Nova Scotia B3J 2S7 Canada
tel.: 902-426-5933 fax: 902-426-1489
bdt%hxlfhm%dfosf@sfnet.dfo.ca

David Townsend
University of Maine
Department of Oceanography
5741 Libby Hall
Orono, ME 04469-5741
tel.: 207-581-4367 fax: 207-581-4388
davidt@maine.maine.edu

Bruce Tripp
Woods Hole Oceanographic Institution
Rinehart Coastal Research Center
193 Oyster Pond Road, MS #2
Woods Hole, MA 02543-1525
tel.: 508-289-2900 fax: 508-457-2172
btripp@whoi.edu

Page Valentine
U.S. Geological Survey
Quisett Campus
384 Woods Hole Road
Woods Hole, MA 02543
tel.: 508-457-2239 fax: 508-457-2310
pvalentine@usgs.gov

Robert Wall
University of Maine
Center for Marine Studies
5715 Coburn Hall, Room 14
Orono, Maine 04469-5715
tel.: 207-581-1435 fax: 207-581-1426
robert_wall@voyager.umeres.maine.edu

Gordon Wallace
University of Massachusetts at Boston
Environmental Coastal and Ocean Sciences Program
Boston Harbor Campus
100 Morrisey Blvd.
Boston, MA 02125
tel.: 617-287-7440 fax: 617-287-7474
wallace@umbsky.cc.umb.edu

John Williamson
New Hampshire Commercial Fisheries Association
201 Wells Rd.
Kennebunk, ME 04043
tel.: 207-967-5340

James Wilson
University of Maine
School of Marine Sciences
Winslow Hall
Orono, ME 04469-5782
tel.: 207-581-3101 fax: 207-581-4278
jwilson@maine.maine.edu

Contributor's Name Index

Contributor's Name Index

Key Words Index

This index lists key words supplied by those authors of poster abstracts who submitted them and also includes an attempt by the editors to identify appropriate keywords for the management comments and the plenary papers. The Working Group Reports were not indexed. The keyword index is therefore not a comprehensive index.