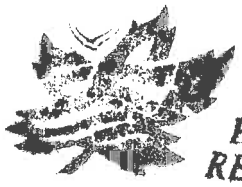

EFFECTS OF CHANGES IN SEA LEVEL AND TIDAL RANGE ON THE GULF OF MAINE – BAY OF FUNDY SYSTEM

Proceedings of a joint conference of the

FUNDY ENVIRONMENTAL STUDIES COMMITTEE

and the

NEW ENGLAND ESTUARINE RESEARCH SOCIETY

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PREFACE

"For now we see through a glass, darkly; but then face to face:"(1)

This volume constitutes the proceedings of the first joint conference of two scientific organizations sharing a common border, a common oceanographic system, and a common interest in the characteristics of estuarine and coastal systems. The New England Estuarine Research Society originated in 1969 to provide a forum for communication between scientists interested in estuaries of the New England area. Its membership is largely based at U.S. universities, colleges and research laboratories. The Fundy Environmental Studies Committee arose in 1977 to provide a similar framework for information exchange and, more importantly, practical cooperation between scientists interested in the Bay of Fundy - an interest group that was generated by proposals for large scale development of tidal power in the upper Bay of Fundy. The focus of this group was much more pragmatic because of the perception that decisions regarding tidal power development might be made within a few years(2). Although the only tidal power development yet to occur has been the pilot project at Annapolis Royal, Nova Scotia, the value of the Fundy Environmental Studies Committee may be measured in terms of the rapid accumulation of knowledge concerning the unique macrotidal estuaries at the head of the Bay. From being one of the least known of coastal ecosystems in eastern Canada a decade ago, the upper Fundy region may now be the best known of Canada's many estuaries(3). Undoubtedly the specific focus and extensive cooperative effort involving more than one hundred scientists played a major role in that development.

With settlement of the Canada-U.S. boundary dispute over Georges Bank, the mounting concerns over management and conservation of fisheries in the Gulf of Maine, and recognition of the limited knowledge of the Gulf and outer Bay of Fundy, it was natural that scientists would seek ways to initiate essential research programmes in the region. The joint FESC-NEERS conference held at Yarmouth, N.S. on 24-25 October 1985, which was financially supported by the Atlantic Provinces Council on the Sciences (APICS) and Environment Canada, was one such step.

The conference consisted of a series of invited presentations around the theme of the probable effects of rising sea level and increasing tidal range on ecosystems of the Bay of Fundy - Gulf of Maine system. As Titus and Wells point out, an inexorable rise in sea level of 2-3 mm yr^{-1} may be accelerating

as a result of the greenhouse effect. Such a rise has serious ecological and economic implications for all coastal systems and communities. These demand that coherant planning processes be initiated without delay. Greenberg and DeWolfe's papers build on Greenberg's original mathematical model of the Gulf and Bay. On the one hand they describe aspects of the natural variability of physical features of the system - tides, currents, waves, etc. - and on the other hand explore the extent to which the negative effects of a tidal power development might be ameliorated by changing operational procedures of the development.

As with Fundy, the biological constituents of the Gulf of Maine are now poorly known. Gordon reviews the major sources of primary production of the system, and Larsen the benthic resources. It is apparent from these two articles that much remains to be done just to document the biological resources and productivity of the region. An important first step, however, has already been taken in Campbell's development of an ecosystem model for the Gulf region. Although presently limited to the pelagic zone, a generalized ecosystem model will form a sound foundation for development of comprehensive, cooperative research programmes. This was a lesson that the Fundy Environmental Studies group learned perhaps a little late(4). It is interesting to note that Campbell's model emphasizes the importance of tidal mixing in stimulating primary production and, consequently, fish production in some portions of the Gulf, but not all. Since rising sea level is associated with increased tidal range(5), and the relationship between tidal mixing and tidal range is non-linear(6), some enhancement of coastal production may be expected over time. In their review of implications for regional fisheries, Rulifson and Dadswell concur with this interpretation, although they also point out the extensive interactions that take place between numerous environmental variables, and consequently the difficulty of interpreting historical data. This makes a very convincing argument for an enlarged and integrated programme of research into the fisheries resources of the Bay of Fundy - Gulf of Maine region. Although not part of the original programme, the Addendum by Bleakney is a timely reminder that in estuaries dynamic processes of erosion and sedimentation lead to continual reshaping of estuarine morphometry. In the upper Bay of Fundy, tuning of the estuary resulting in elevation of tidal range may have been a greater source of change than sea level rise - and certainly one with a complex history.

The programme was completed with a number of contributed papers and posters, the abstracts or titles of which are included in this volume. They testify to the diversity of talent and interest in estuarine and coastal science in this northeast corner of North America. They also assure us that if the problems of management and jurisdiction of this most important and remarkable coastal system prove intractable, it will not be for lack of scientific potential. It is to be hoped that this first small step will be the foundation for extensive cross-boundary scientific cooperation in the years to come.

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1. GREENHOUSE EFFECT AND SEA LEVEL RISE: AN UPDATE

James G. Titus and John Bruce Wells

INTRODUCTION

Around the Bay of Fundy, unlike most of the rest of the coast, people have focused far more on the implications of changes in tidal range than on changes in sea level. In an area where tidal fluctuations are three to sixteen meters, while the sea is rising at two to three millimeters per year, this focus is understandable--especially given the prospect of tidal power plants that could change the tidal range by 10 percent.

Nevertheless, a growing body of evidence suggests that in the coming decades rising sea level will be an increasingly important issue. Increasing concentrations of carbon dioxide, methane, chlorofluorocarbons, and other gases released by human activities are expected to warm the earth several degrees; such a warming could raise sea level roughly one meter in the next century by expanding ocean water, melting mountain glaciers, and perhaps eventually, causing polar glaciers to slide into the oceans. Fortunately, much of the research that has been conducted to assess the consequences of tidal changes will also be useful for understanding the consequences of sea level rise.

In this paper, we discuss the basis for expecting a rise in sea level, summarizing previous studies and presenting updated sea level scenarios based on the recently released report Glaciers, Ice Sheets, and Sea Level by the U.S. National Academy of Sciences' Polar Research Board(5). We then discuss studies conducted by the U.S. Environmental Protection Agency (EPA) on the impacts of future sea level rise on various communities in the United States. Although EPA has not assessed the potential impacts on the Bay of Fundy area, we conclude with a discussion of the types of impacts that need to be investigated in this region.

PREVIOUS STUDIES

Although sea level rose about one meter per century from 18,000 years ago until 6,000 years ago, it has been relatively stable in recent centuries. Similarly, although the earth has warmed about 4C^{o} since the last ice age, global temperatures have fluctuated by only about 1C^{o} in the last thousand years. The next century, however, may be very different. The human race is releasing gases into the atmosphere that are likely to warm our planet another four degrees in the next century by a mechanism commonly known as the "greenhouse effect."

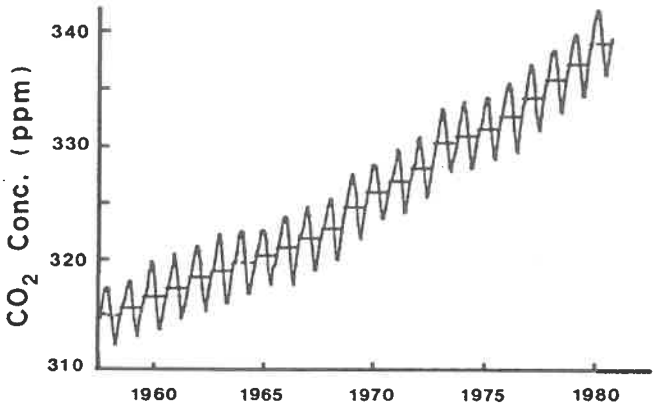
Trace gases that absorb radiation, such as CO_2, are critical components of the earth's atmosphere. Our planet would be too cold to support life were it not for the greenhouse effect of the atmosphere. Since the beginning of the industrial revolution, however, the level of CO_2 in the atmosphere has been increasing as a result of the combustion of fossil fuels and deforestation. Although precise measurements only began in 1957, indirect techniques such as the analysis of air trapped in polar ice cores show that CO_2 concentrations have increased about 25 percent since the middle of the 19th century. Energy experts generally expect the level of CO_2 to be double its preindustrial concentration during the third quarter of the twenty-first century.

The prospect that society is altering the geophysical properties of the atmosphere spurred scientists to investigate the climatic effects of such increases, particularly after 1960. By 1979 sufficient evidence had accumulated for the National Academy of Sciences (NAS) to conclude that the earth is likely to warm substantially(1). The NAS estimated that a doubling of atmospheric CO_2 (or equivalent increases in other trace gases) would eventually raise the average global surface temperature by 1.5 to 4.5^{o}C, with more warming at high latitudes and less warming near the equator. Other scientific groups have reached similar conclusions(2).

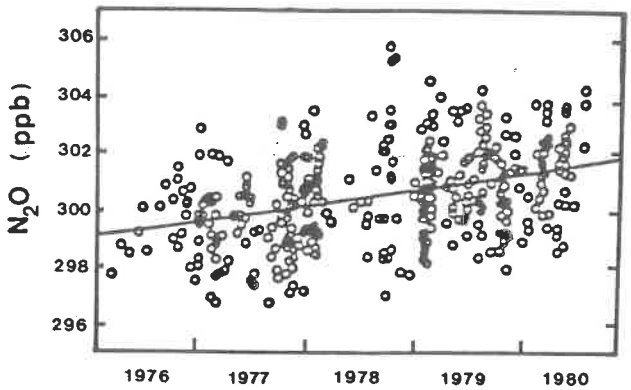
Although researchers focused their early attention on CO_2, scientists have concluded in the last few years, that other trace gases, such as methane, nitrous oxide, and chlorofluorocarbons, may be equally important. Various basic and diverse activities produce these trace gases. For example, growing rice, raising cattle, mining minerals, burning fossil fuels and clearing forests all release methane. Combustion of fossil fuels and fertilization of crops release nitrous oxide. Chlorofluorocarbons are linked to more advanced processes: cleaning computer chips and use of such products as insulation, refrigerators and air conditioners release these gases. Other economic activities are increasing the emissions of other radiatively active trace gases (See Fig. I-1).

One of the effects of warmer temperatures would be a rise in sea level, which was estimated for the first time in 1983 by two

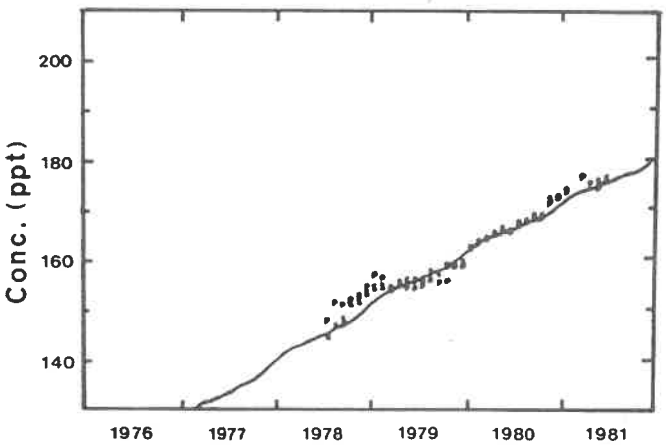
Fig. 1-1. Concentrations of selected greenhouse gases over time.



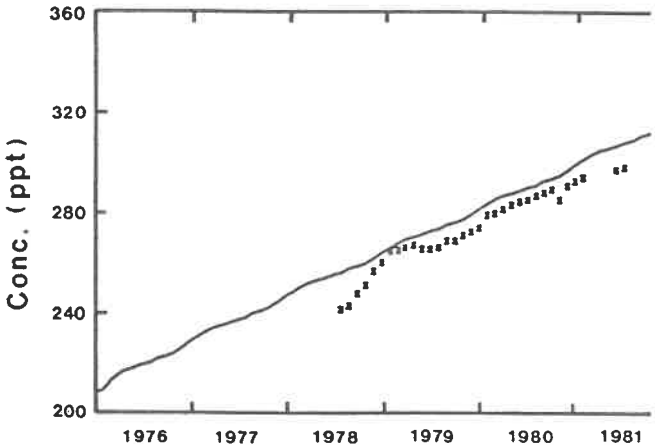
Carbon Dioxide Concentrations
Source : NOAA



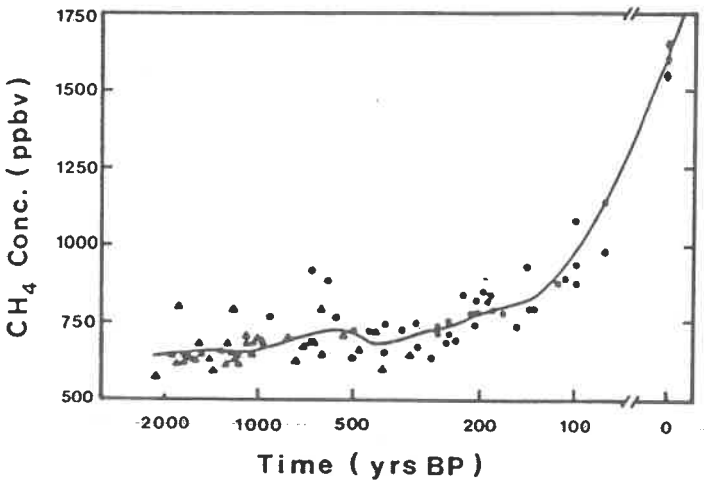
Nitrous Oxide Concentrations
Source : Weiss (1981)



CFC11 Concentrations
Source : Cunnold et al. (1983a)



CFC12 Concentrations
Source : Cunnold et al. (1983b)



Methane Concentrations
Source : Rassmussen and Khalil (1984)

independent reports. In the National Academy of Sciences report Changing Climate, Revelle estimated that the thermal expansion of ocean water would raise sea level about 30 cm in the next century, that melting of Greenlandic and alpine glaciers would each add 12 cm, and that other factors responsible for current trends would continue for a total rise of 70 cm(3). Although he stated that Antarctica could contribute two meters per century to sea level starting around 2050, Revelle did not add that contribution to his estimate.

In a report by the Environmental Protection Agency entitled Projecting Future Sea Level Rise, Hoffman et al, stated that the uncertainties regarding the factors that could influence sea level are so numerous that a single estimate of future sea level rise is not practical(4). Instead they specified high, medium, and low estimates for fossil fuel use, the absorption of carbon dioxide through natural processes, future emissions of other greenhouse gases, the global warming from a doubling of greenhouse gases, the diffusion of heat into the oceans, and the impact of ice and snow. They concluded that if all the low estimates prove correct, sea level will rise 13 cm by 2025 and 24 cm by 2050. If all the high estimates are correct, the sea will rise 55 cm by 2025 and 117 cm by 2050. However, because it is unlikely that either all the high or all the low estimates will prove to be correct, the authors concluded that the rise will be between 26 and 39 cm by 2025 and between 53 and 79 cm by 2050. They stressed however, that the absence of glacial process models severely limited the confidence that could be placed in this first set of scenarios.

UPDATED SCENARIOS

In the summer of 1985, the National Academy of Sciences Polar Research Board released the first comprehensive study to model the glacial response to a global warming(5). Accordingly, it seemed like a good time to update previous scenarios of sea level rise. This time, however, we do not estimate extremely high or low scenarios but focus only on the likely range of future sea level rise.

Emissions and Concentrations of Greenhouse Gases

Many groups have projected the future concentrations of greenhouse gases, based on the observed relations between emissions and basic societal measures such as population and gross national product. To ensure that their projections are conservative, researchers usually assume that population and economic growth will decelerate. In addition, they often assume that technological improvements will reduce emissions. Because projections are inherently uncertain, researchers usually report low, medium, and high estimates. Table 1-1 summarizes published estimates of future concentrations.

Table I-1. LOW AND HIGH PROJECTIONS OF TRACE GASES BY RESEARCHERS

Average percent increase in concentrations: 1980-2030

Greenhouse GAS	NAS (1983)	Seidel & Keyes (1983)	Ramanathan *et al.* (1984)	Edmonds *et al.* (1984)	Wuebbles *et al.* (1984)	Quinn *et al.*, RAND (1984)	Gibbs & Trippe ICF (1984)
CO_2	0.4,0.7	0.6	--	0.5,0.8	--	--	--
CH_4	--	--	0.3,1.5	--	0.0,1.0	--	--
N_2O	--	--	0.3,0.8	--	0.0,0.3	--	--
CFC_{11}	--	--	2.0,4.8	--	--	3.5,4.9	2.9,11.5
FC_{12}	--	--	2.3,5.1	--	--	3.3,4.3	3.4,6.0
Others:							
SO_2	--	--	0.0,1.4	--	--	--	--
CF_4	--	--	2.1,3.0	--	--	--	--
C_2F_6	--	--	1.8,4.6	--	--	--	--
$CHC1F_2$	--	--	3.8,6.9	--	--	--	5.8,8.6
$CC1F_3$	--	--	3.5,5.3	--	--	--	--
CH_2C1_2	--	--	2.4,4.6	--	--	--	--
$CHC1_3$	--	--	1.4,4.6	--	--	--	--
$CC1_4$	--	--	0.9,2.2	--	--	2.4	--
CH_3CC1_3	--	--	3.2,6.5	--	--	--	--
$CBrF_3$	--	--	2.2,4.6	--	--	7.2	--
C_2H_2	--	--	0.0,2.0	--	--	--	--

Based on this body of research, we construct two scenarios for trace gas emissions and concentrations. To reflect our uncertainty in projecting the distant future, we divide our estimates into three time periods. We are most certain of the near future, 1985 to 2000, which we call our "forecast period." In this period we rely on well-accepted forecasts of current market trends. As unforseeable events deflect these trends, our uncertainty increases. Nonetheless, we can place reasonable bounds on such basic forces as population growth and overall economic activity for the period from 2000 to 2030, which we call the "scenarios period." Beyond 2030, we lose confidence in our projections of population and economic growth. All we can do is test various contingencies; thus we call the period from of 2030 to 2060 the "contingency period."

For projecting carbon dioxide emissions we adopt the NAS projections(6). Our low case is drawn from the NAS 25th percentile, and our high case from the NAS 75th percentile. The CO_2 concentrations which result from these emissions will depend on the global carbon cycle. Following Seidel and Keyes(7), who evaluated the results of the Oak Ridge National Laboratory Carbon Cycle Model, we assume that the fraction of carbon emissions which remains airborne as CO_2 will rise as global warming alters the carbon cycle.

To project the future emissions of the most widely used chlorofluorocarbons, $CFC\text{-}11$ and $CFC\text{-}12$, we use scenarios developed by Quinn et al.(8) of the RAND Corporation. These researchers found that in the developed countries $CFC\text{-}11$ and $CFC\text{-}12$ use has grown approximately three times as fast as national income. In the absence of new governmental regulations, this relation should continue. We base our estimate of the resulting concentrations on the work of Rind and Lebedeff(9), who constructed an exponential decay model to fit past atmospheric measurements.

Our projections for methane and nitrous oxide concentrations fall within the range reported by Ramanathan et al.(10) and Wuebbles et al.(11). Numerous other trace gases, linked to such diverse economic activities as aluminum smelting and dry cleaning, may affect the climate. We have adopted the concentration projections of Ramanathan et al.(11).

Future Global Warming

Although the NAS estimates that the earth's equilibrium response to a doubling of greenhouse gases would be a 1.5 to 4.5 degrees warming, the major climate models(12) show a narrower uncertainty ranging from 2 to 4°C; we adopt this narrower range.

To estimate the direct radiative forcing of greenhouse gases we use the model developed by Lacis et al. of the Goddard Institute for Space Studies(13). We modify the model to include many of the trace gases identified by Ramanathan et al.(14).

Table I-2 presents the trace gases included in the modified model. Because we do not include possible changes in water vapor and the distribution of ozone, we may underestimate the total radiative forcing.

The timing of future temperature increases will depend on the absorption of heat by the oceans. Estimating this absorption is difficult because we cannot fully describe the oceanic mechanisms by which heat is transported. Based on transient tracer analysis, Broecker and Peng(15) developed an average eddy diffusion coefficient for the oceans of 1.7 cm/sec^2. We use this value, accepted by many as a reasonable surrogate measure, at least for small perturbations.

For our low and high scenarios, Figure I-2 shows the global temperature changes that the model predicts for each time period. For our market period of 1980 to 2000, we project an increase in the average global temperature of 0.2 to 0.4 degrees. By the end of our scenario period in 2030, the increase is from 0.7 to 1.6 degrees. In 2060, the end of the contingency period, the temperature increase is 1.4 to 3.4 degrees. Figure I-3 shows the projected "unrealized warming," i.e., warming that will eventually occur but has not yet occurred because oceans delay the warming. The estimates of unrealized warming imply that by 2060, society will have released enough gases for a total equilibrium warming of 2.5 to 9 degrees. This unrealized warming implies that if society waits until the warming is observed before taking measures to limit the warming, it will be too late to avoid additional warming of several degrees.

Future Sea Level Rise

Estimates of global sea level rise must consider all the processes by which global temperature rise can increase oceanic water volume. Estimates for particular regions must also consider changes in such local conditions as land subsidence and construction. For example, along the coast of Maine one must add 1-2 mm/yr to the projections of global sea level rise.

Global temperature rise can elevate the sea level in four ways: by raising the temperatures of the oceans, which expands the volume; by melting alpine glaciers, which adds water to the ocean basins; by melting the fringes of polar glaciers (Greenland and Antarctica) sufficiently to exceed the effects of possible increases in snowfall associated with a global warming; and by increasing the discharge of ice from Greenland and Antarctica ice caps into the ocean. Our degree of certainty about each process varies.

Oceanic absorption of heat is the major force that delays global warming. Absorbed heat, however, is the primary contributor of sea level rise. We can estimate the rise by applying expansion coefficients to the estimated annual increments of heat. While a three dimensional ocean model would

Table 1-2. SUMMARY OF SCENARIOS USED IN THIS STUDY

	Average Growth Rates (Percent) in Concentrations					
	Forecast Period (1980 to 2000)		Bounding Period (2000 to 2030)		Contingency Period (2030 to 2060)	
	Low	High	Low	High	Low	High
CO_2	0.33	0.47	0.54	0.77	0.61	0.94
CH_4	0.70	1.40	0.70	1.40	0.70	1.40
N_2O	0.20	0.25	0.20	0.25	0.20	0.30
CFC_{11}	5.26	5.87	2.48	4.21	1.52	2.75
CFC_{12}	4.60	4.92	2.49	3.85	1.70	2.87

Other trace gases: SO_2, CF_4, C_2F_6, $CHC1F_2$, $CC1F_3$, CH_2C1_2, $CHC1_3$, $CC1_4$, CH_3CC1_3, $CBrF_3$, C_2H_2

Low: Linear interpolation to Ramanathan et al. (1984) best guess in 2030; constant thereafter.

High: Linear interpolation to Ramanathan et al. (1984) high estimate in 2030; extrapolated thereafter.

Fig. I-2.

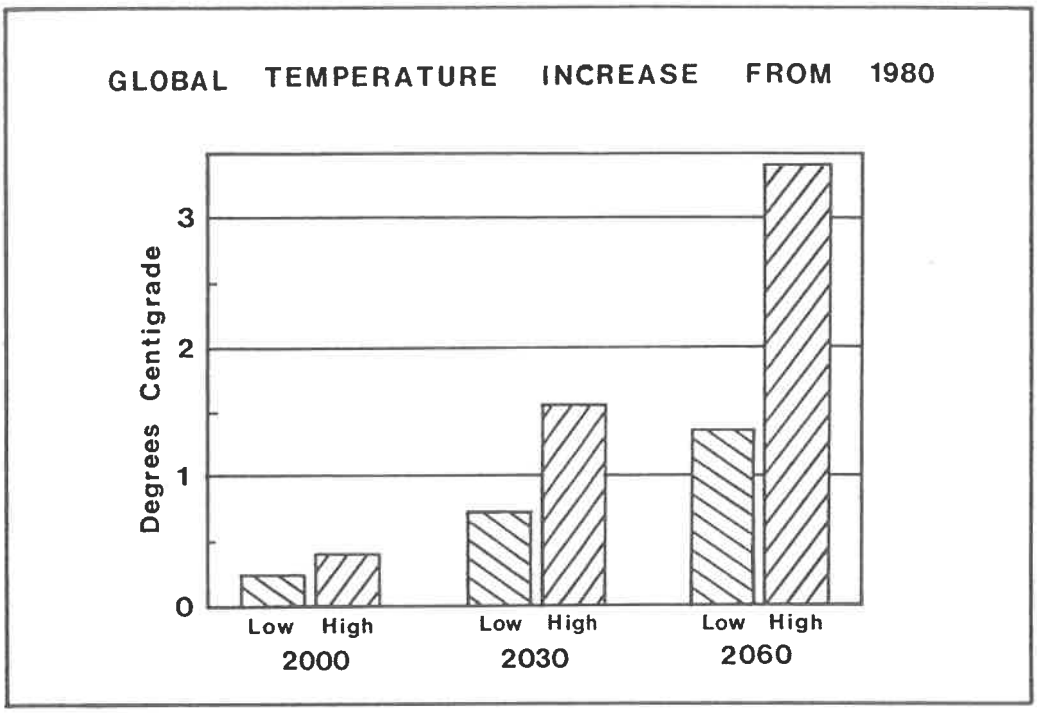
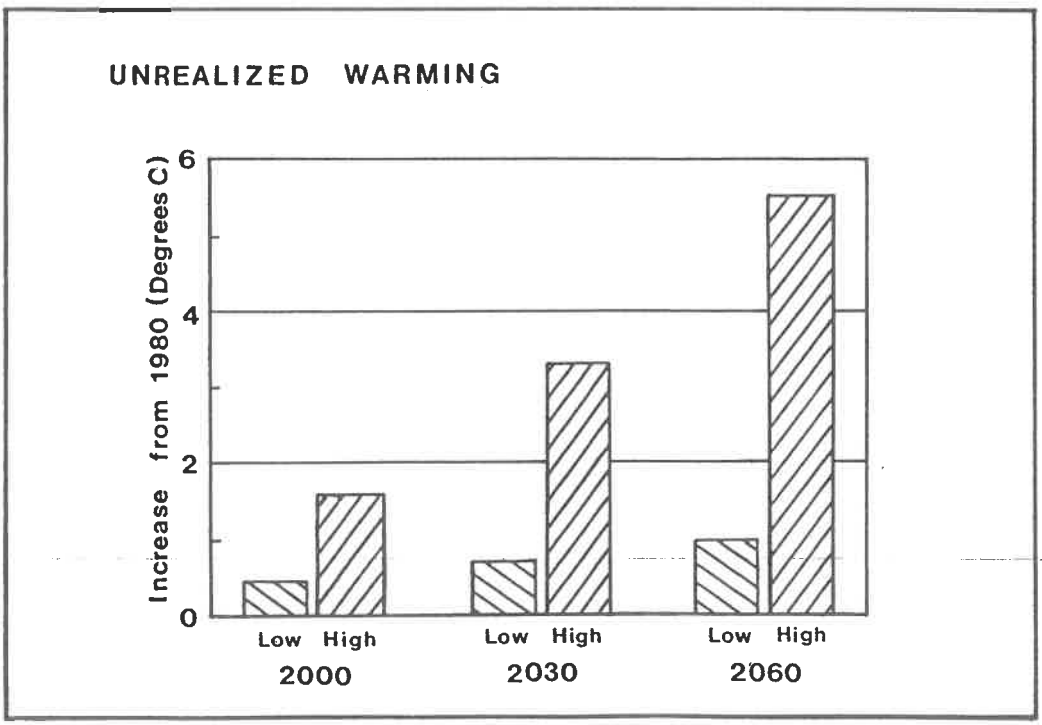

GLOBAL TEMPERATURE INCREASE FROM 1980
Degrees Centigrade
0
1
2
3
Low High
2000
Low High
2030
Low High
2060

Fig. I-3.


UNREALIZED WARMING
Increase from 1980 (Degrees C)
0
2
4
6
Low High
2000
Low High
2030
Low High
2060

provide the most accurate result, comparative analyses show little difference in the results of three and one dimensional models(16). We therefore use the one dimensional model of heat diffusion developed by Lacis et al.(17). Figure I-4 displays our results. We estimate that by the year 2000, thermal expansion will raise sea level 2 to 4 cm; by 2030, 7 to 15 cm; and by 2160, 15 to 35 cm.

Alpine glaciers will probably be the next most important source of sea level rise in the next seventy-five years. Meier(18) estimates that the global temperature increase of 0.5C° in the last 100 years caused meltwater from alpine glaciers to contribute approximately 28 mm to global sea level. He suggests that future temperature increases will similarly correlate with increases in alpine meltwater. We use this relation to yield the estimates shown in Figure I-4; a contribution from alpine meltwater of 1.3 to 2.2 cm by 2000; 3.9 to 8.3 cm by 2030; and 7.2 to 18.3 cm by 2060.

Meltwater from Greenland may also contribute to sea level rise. In the recent Polar Research Board report, Binschandler(19) conducts a mass balance of Greenlandic ice and links changes in each process to changes in surface temperature. In our model, we assume that the contribution to sea level in centimeters will be the increase in Greenland's temperature raised to the 1.5 power, multiplied by 0.248; this equation approximates Binschandler's results. Figure I-4 displays our results: 0.0 to 0.1 cm by 2000, 0.5 to 1.4 cm by 2030, and 2.0 to 6.7 cm by 2060.

Researchers have not yet estimated the contribution of Antarctic meltwater to future sea level rise. One climate model(20) indicates that doubling CO_2 could increase the rate of meltwater from Antarctica enough to add one meter per century to global sea level. However, none of the models realistically simulates precipitation and surface runoff, and one should not take that result as a quantitative estimate. It does suggest that the forces which influence surface meltwater runoff should be more carefully analyzed in the future. In this paper we assume the contribution from Antarctic meltwater to be zero.

The remaining possible contributor to sea level rise is enhanced ice discharge from Greenland and Antarctica, the areas that have received the most attention in the popular press, but which are the most uncertain and long-range. Because the physical processes that will influence ice discharge from Greenland are less well understood than those of Antarctica, we include no estimates for Greenland.

Most attention concerning Antarctica has focused on the West Antarctic Ice Sheet which is buttressed by large floating ice shelves that appear to regulate the rates of ice discharge from the inland sheet. Much of the West Antarctic Ice Sheet is grounded below sea level. If warming polar waters thin the

surrounding ice shelves, the inland ice sheet could begin to move more rapidly into the sea.

If the entire West Antarctic Ice Sheet was to collapse into the ocean, the sea would rise approximately 6 meters. However, even extreme conditions of climatic warming could not overcome the physical constraints on the rate at which the ice could either melt or flow into the ocean. Current estimates suggest that complete collapse of this ice sheet would take at least 300 years, and possibly 500 years or longer. Although this process might be slow, it might also be irreversible.

In the recent Polar Research Board report, Thomas(21) analyses possible contributions from antarctic ice discharge. His analysis shows that physical constraints delay most of the ice discharge until after 2040. His estimates for the year 2100 vary from an unlikely 2 meters to a "most likely" 24 cm. Within the time frame of our analysis, his estimates of the contribution to total sea level rise do not vary greatly. Figure I-4 presents estimates of sea level rise from this source: no contribution before 2000; 0.4 to 2.3 cm by 2030; and 2.8 to 43.6 cm by 2060. By studying Figure I-4, the reader may gain some insight into the magnitude and sources of sea level rise over time. Figures I-5, I-6, and I-7 allow a closer examination of sea level rise for each time period. Table I-3 shows the effect of varying ocean heat absorption from its assumed values by a factor of 2: a change in relative contribution from the different processes, but not in total sea level rise. These estimates do not include any contribution from Greenland ice discharge or Antarctic meltwater runoff, an omission that needs to be remedied.

The updated scenarios imply that sea level is likely to rise 4 to 6 cm by 2000, 12 to 27 cm by 2030, and 27 to 104 cm by 2060. Although new information has caused us to change many of the assumptions underlying the 1983 report Projecting Future Sea Level Rise(22), the major change in our results is that glacial processes do not appear as likely to contribute significantly to sea level rise in the near term. The analysis by the Polar Research Board suggests, however, that the rise in sea level after the middle of the next century is likely to be of the same order as projected in the earlier reports.

EPA STUDIES OF THE IMPACTS OF FUTURE SEA LEVEL RISE

Only a few studies have estimated the economic and environmental impacts of future sea level rise. A multidisciplinary team of researchers examined the potential impacts at Charleston, South Carolina(23). The research team considered inundation, erosion, storm surges from increased ocean flooding, and saltwater intrusion.

In Charleston, most of the land low enough to be inundated by a one to two meter rise in sea level is marsh or swamp. Kana,

Fig. I-4.

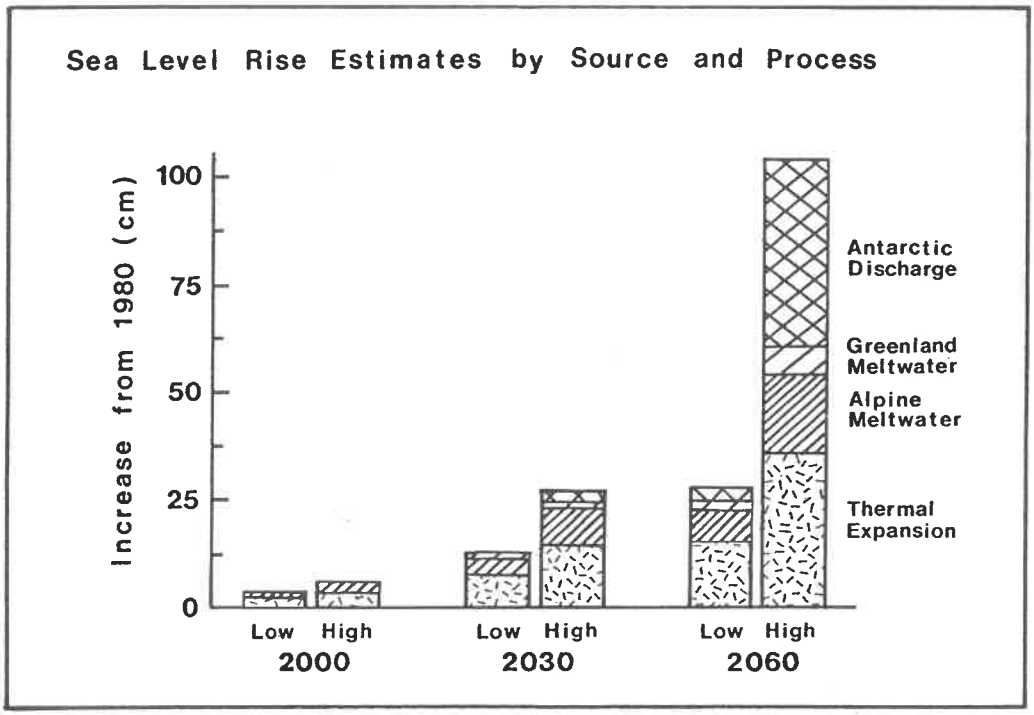

Sea Level Rise Estimates by Source and Process
Increase from 1980 (cm)
100
75
50
25
0
Low High
2000
Low High
2030
Low High
2060
Antarctic Discharge
Greenland Meltwater
Alpine Meltwater
Thermal Expansion

Fig. I-5.

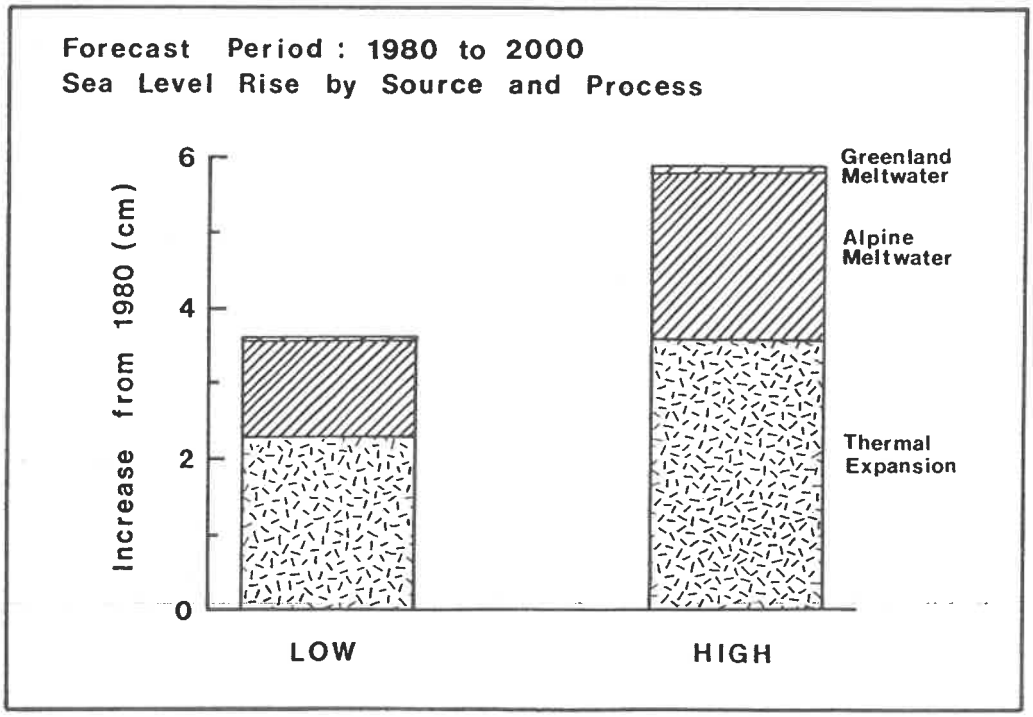

Forecast Period : 1980 to 2000
Sea Level Rise by Source and Process
Increase from 1980 (cm)
6
4
2
0
LOW
HIGH
Greenland Meltwater
Alpine Meltwater
Thermal Expansion

Fig. I-6.

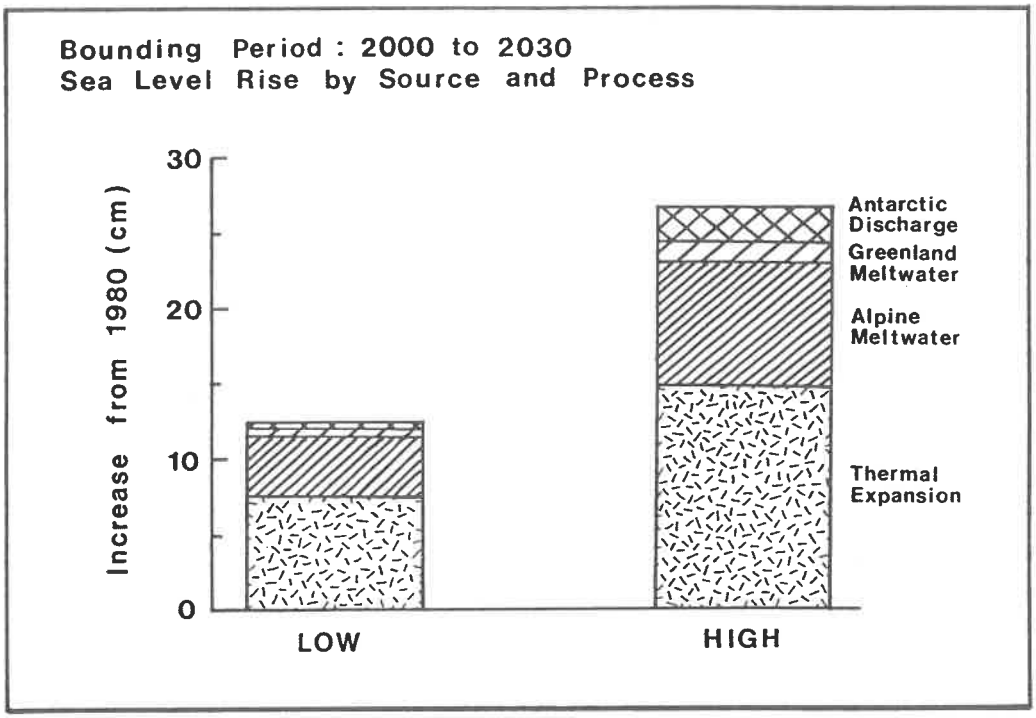

Bounding Period : 2000 to 2030
Sea Level Rise by Source and Process
Increase from 1980 (cm)
30
20
10
0
LOW
HIGH
Antarctic Discharge
Greenland Meltwater
Alpine Meltwater
Thermal Expansion

Fig. I-7.

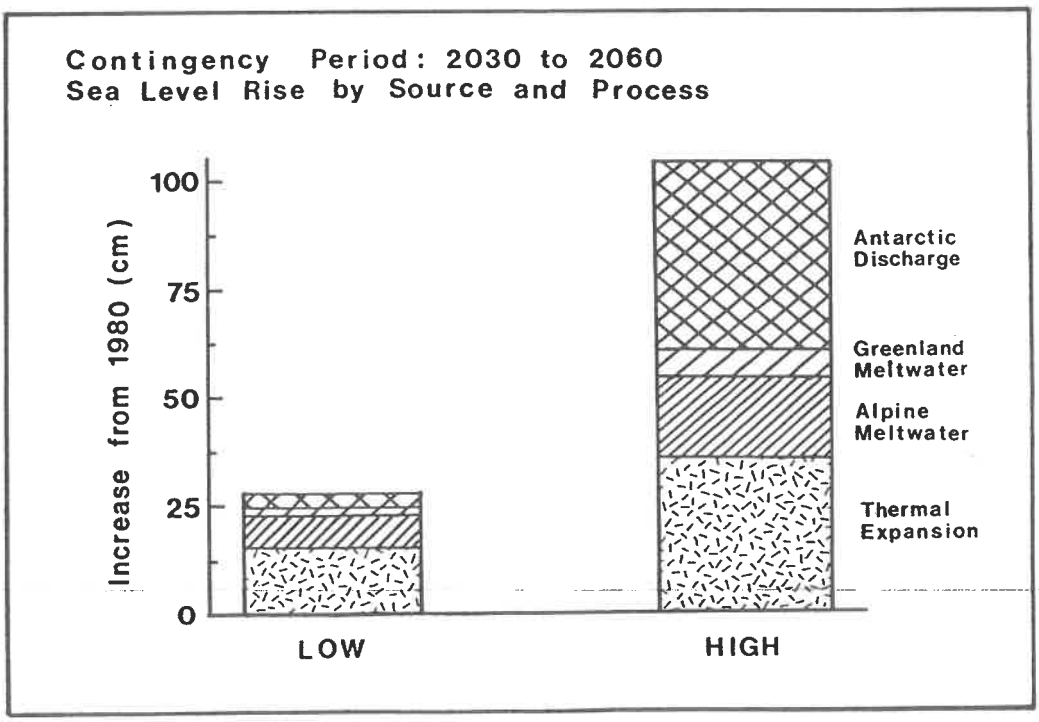

Contingency Period: 2030 to 2060
Sea Level Rise by Source and Process
Increase from 1980 (cm)
100
75
50
25
0
LOW
HIGH
Antarctic Discharge
Greenland Meltwater
Alpine Meltwater
Thermal Expansion

Table I-3. SENSITIVITY TO OCEANIC HEAT ABSORPTION SEA LEVEL RISE BY SOURCE AND PROCESS
(cm from 1980)

	Forecast Period (1980 to 2000)			Bounding Period (2000 to 2030)			Contingency Period (2030 to 2060)		
	Diffusivity "k" (cm/sec^2)			Diffusivity "k" (cm/sec^2)			Diffusivity "k" (cm/sec^2)		
	.85	1.7	3.4	.85	1.7	3.4	.85	1.7	3.4
LOW SCENARIO									
Thermal Expansion	1.96	2.28	2.57	6.47	7.59	8.59	13.03	15.38	17.44
Alpine Meltwater	1.42	1.28	1.15	4.24	3.87	3.56	7.84	7.24	6.76
Antarctic Discharge	0.00	0.00	0.00	0.36	0.36	0.36	2.78	2.78	2.78
Greenland Meltwater	0.05	0.04	0.04	0.59	0.51	0.44	2.24	1.97	1.75
TOTAL*	3.43	3.60	3.76	11.66	12.33	12.95	25.89	27.37	28.73
HIGH SCENARIO									
Thermal Expansion	3.25	3.60	3.89	13.25	14.66	15.89	32.01	35.60	38.71
Alpine Meltwater	2.54	2.18	1.88	9.64	8.29	7.15	21.08	18.27	16.00
Antarctic Discharge	0.00	0.00	0.00	2.30	2.30	2.30	43.63	43.63	43.63
Greenland Meltwater	0.11	0.09	0.07	1.74	1.39	1.11	8.29	6.66	5.40
TOTAL*	5.90	5.88	5.84	26.93	26.64	26.45	105.01	104.16	103.74

* Total sea level rise does not include Antarctic meltwater or Greenland ice discharge.

Baca, and Williams(24) estimate that a 1.5 m rise in sea level would drown approximately 80 percent of the wetlands in Charleston, in spite of the marshes' ability to accrete vertically through sedimentation and peat formation. Their estimates also assume that houses immediately inland of today's marsh are moved out of the area so that the new marsh can form inland as sea level rises. If developed areas are protected with levées and bulkheads, new marsh will not form and the area could lose 90 percent of its wetlands.

Gibbs(25) estimates that the economic impact in Charleston for a 1.5 m rise would be 1.9 billion dollars by 2075 -- 26 percent of the total economic activity in the area -- if current policies continue and the area fails to anticipate the future consequences of sea level rise. However, Gibbs also estimates that if the area anticipates the rise and modifies its land use policies and building codes, the impact could be reduced by over 60 percent. Studies in Galveston, Texas show similar results(26). In the part of Galveston not protected by a seawall, much of the island is lost to inundation or erosion, and the economic impacts on the area could be reduced from $965 million to $550 million through advanced planning.

Rising sea level also increases storm flooding in coastal areas. The higher sea level provides a higher base on which storm surges can build. Moreover, the erosion caused by sea level rise can leave properties closer to the water and more vulnerable to storm damage. Kana et al.(27) estimate that a 1 m rise in sea level would increase the portion of the Charleston area within the 10-year floodplain from 30 percent to 45 percent, and a 1.5 m rise would increase this portion to over 60 percent, the current size of the 100-year floodplain. Leatherman(28) estimates that in Galveston a 1.5 m rise would allow a 100-year storm to overtop the Galveston Seawall and put almost the entire area within the 100-year floodplain.

Although inundation will account for most of the land loss in areas with low wave energies such as Charleston, land along the open coast above sea level can erode as sea level rises. This possibility is particularly important to ocean resort communities with extremely high property values. Everts(29) examines the situation at Ocean City, Maryland, the largest beach resort near Washington, D.C. Using an approach derived from Bruun(30) he estimates that for every centimeter the sea rises, the beach at Ocean City would erode approximately 65 centimeters. However, because significant losses of sand due to longshore transport are expected, he projects that the 34-cm rise he uses would result in shoreline erosion of approximately 70 m by 2025 (a large percentage of the beach). Leatherman(31) and Kriebel and Dean(32) arrive at similar estimates of the sand needed to maintain Ocean City. Using the results of these analyses, Titus(33) concluded that if sea level is going to rise, it would be better for the community to address current erosion problems by pumping sand onto its beach than by continuing to build

groins, a conclusion that was subsequently endorsed by the State of Maryland.

A rise in sea level would also increase the salinity of rivers, bays, and aquifers. Hull and Tortoriello(34), for example, estimate that even a 13 cm rise in sea level could cause the 250 ppm isochlor to migrate upstream 2-4 kilometers in the Delaware River. In a draft report prepared for the Environmental Protection Agency and the Delaware River Basin Commission(35) the authors estimate that a 73 cm rise would increase salinity enough to threaten parts of Philadelphia's water supply during droughts and contaminate aquifers in New Jersey that are recharged by the Delaware River.

WHAT DOES IT MEAN TO THE BAY OF FUNDY?

The Bay of Fundy area appears to be far less vulnerable to a rise in sea level than most of the U.S. coast. To a large extent the area has steep rocky shorelines rather than the flat sandy shores that characterize much of the Atlantic Coast. Moreover, the large tidal range implies that much of the physical and biological systems are already adjusted to large changes in water levels.

Nevertheless, the impacts will have to be addressed. There are some flat areas and there is development near the high tide line. If some of the coastal interests are concerned about the erosion from a thirty centimeter (one-foot) increase in the tidal range, they have to be concerned about the erosion from a rise in sea level of one meter or more. Interestingly, Maine is one of the few states whose coastal zone management program requires a builder to demonstrate that long-term (100-year) erosion will not threaten a proposed structure. Thus, the prospect of future sea level rise is already relevant to that program.

Perhaps the most important implication of the greenhouse effect, however, is not the rise in sea level but the likely changes in temperatures. If the water warms four degrees (C) one may find completely different species occupying the Bay. Waters now too cold for swimming may be just the right temperature to attract increasing summer visitors, thereby generating a level of coastal development that today would seem unlikely.

The body of research on the implications of tidal power generating plants can be used to gain an understanding of the implications of the greenhouse effect for the Bay of Fundy Region. In some instances, the two phenomena may have additive effects; a rise in sea level and an increase in the tidal range both will result in increased erosion and flooding. On the other hand, Richards(36) suggests that the power plant would lead to cooler winters, which would be offset by the greenhouse effect.

Research on the consequences of the greenhouse effect, like studies on tidal power plants, can be used both to help adaptation to expected environmental changes and to evaluate whether those changes are acceptable. An important difference is that if the power plant is built, we will already understand the likely consequences. By contrast, we are already setting in motion the global warming without understanding the consequences.

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II. TIME AND SPACE VARIATIONS OF WATER LEVELS IN THE BAY OF FUNDY AND GULF OF MAINE

David A. Greenberg

INTRODUCTION

There are many factors governing whether or not a given level of a shore will be covered by water or exposed to the air at a given time of a given day. In the Bay of Fundy and Gulf of Maine, attention is most often focussed on the tides, and frequently any change in sea level is incorrectly lumped under the title "tide." This paper catalogues different processes that influence sea level and estimates magnitudes and scales in time and space.

CURRENTS

Hydraulic Gradients

In the open sea, it is rare that large currents and large current gradients would cause a noticeable draw-down of the sea surface, but in constricted areas this phenomenon is more common. Results from a multigrid model(5,6) indicate that in the narrows by Cape Split the strong tidal currents, peaking at 4 m s^{-1}, lower the mean sea level beside the Cape by as much as 0.5 m. Tidal currents would probably have similar effects around the islands and irregular coastline in the Gulf of Maine. Outside of estuaries, currents other than tidal are probably not strong enough or regular enough to cause this hydraulic effect.

Large Scale Barotropic Currents

Large, steady barotropic currents can cause a set up or set down along a coast. An example of such a current is El Niño, whose arrival is noted by a sea level rise along western South America. In the open ocean, sea level can differ by 1 m across the Gulf Stream. Seasonal mean currents along the east coast of North America also have a sea level signature. In the Fundy-Maine system, the most noticeable effects should be from transport into the system from the Scotian Shelf. Wright *et*

al.(16) indicate that the set up associated with Smith's(14) estimates of average annual inflow are in the order of 2.5 cm (Fig. II-1). Smith noted a pronounced seasonal cycle in which the transport varied from near zero in summer, to twice the annual average in winter(14).

DENSITY EFFECTS

The seasonal transport along the Scotian shelf, mentioned above, is associated with the fresh water runoff from the St. Lawrence. Besides the barotropic effect already noted, steric effects also have an influence. A rough calculation by Drinkwater(personal communication), based on Halifax section data spread over 25 years, indicates a mean annual variation of about 8 cm (Fig. II-2). This baroclinic effect is about the same magnitude as variations from the barotropic current. Similar effects could be found in the Fundy-Maine system due to Saint John River and St. Croix River runoff, but the author is unaware of any detailed calculations.

AIR PRESSURE

A sea surface in isostatic equilibrium with air pressure will exhibit the inverse barometer effect. This means that at a given location, sea level will rise by roughly 1 cm for each 1 mb fall in atmospheric pressure. Thus an atmospheric pressure gradient would be compensated by an opposing sea level slope such that there is no net pressure gradient (or current) in the water. The weather systems may be classified by their central sea level pressure as follows(2):

	Strong	$p \geq 1035$ mb
HIGH	Moderate	1025 - 1034
	Weak	1019 - 1024
	Standard Atmosphere	1013.25
	Weak	1001 - 1005
LOW	Moderate	991 - 1000
	Deep	$p \leq 990$

Given the above, it can be seen that large sea level variations due to air pressure would be in the range 40-50 cm. The relevant scales of this effect depend on the speed, size and track of the different pressure systems.

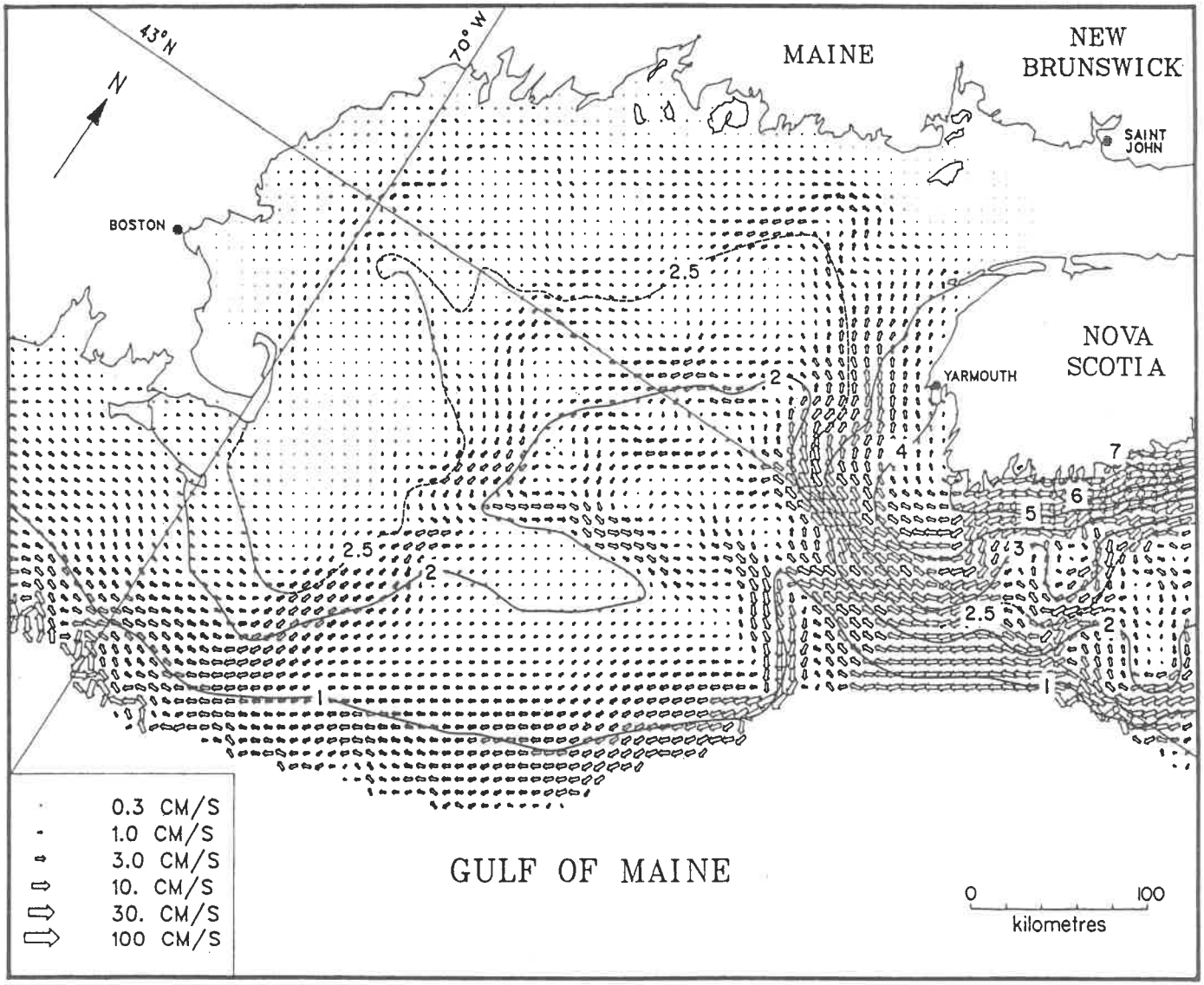


Fig. II-1. The currents and associated set up in the Gulf of Maine from a set up and consequent inflow along the Nova Scotian Shelf (cf. 16).

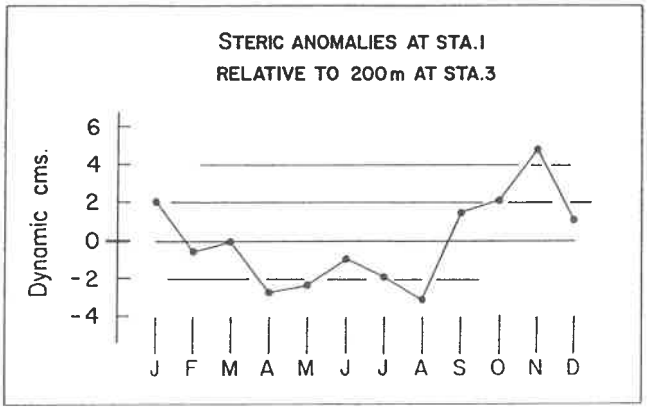


Fig. II-2. The steric anomalies at station 1 relative to 200 m at station 3 of the Halifax section (Drinkwater, personal communication), based on data spread over 25 years. Steric anomalies refer to changes in height of a water column required to maintain a constant pressure at some reference level as the fluid density changes due to temperature or salinity variations.

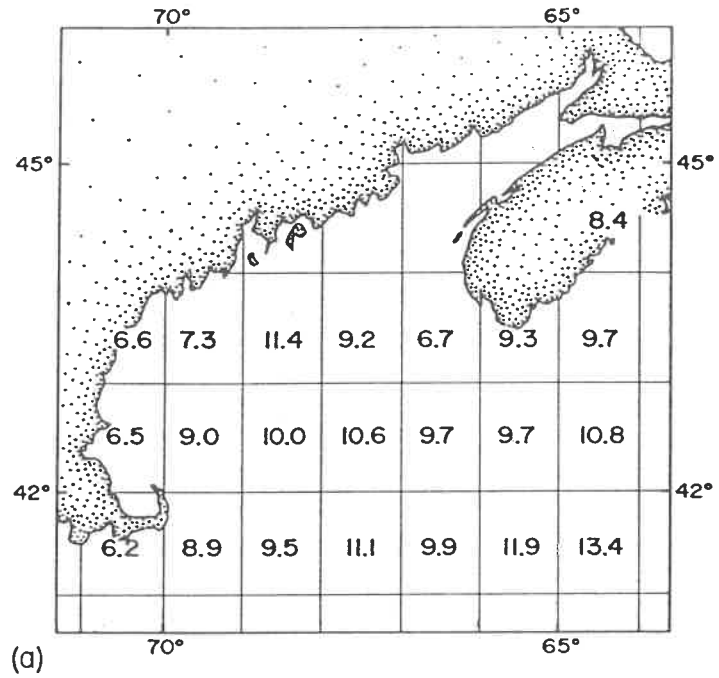
WIND

Surface Waves

Surface waves can be thought of in terms of locally generated waves, and those generated by distant storms which propagate as swell. Strong currents can considerably enhance local wave generation. Periods typically range from 1 to 15 seconds with higher waves associated with larger periods. Because there is a demand for the one, ten and one hundred year significant wave height, statistical estimates of these quantities are made from observations (Fig. II-3), but the data base is rarely adequate and the large uncertainties increase with the extrapolation to longer times. Accuracy to within a factor of two for a 100 year wave might be considered good. The Gulf of Maine is protected by the coast, and the shallows of Nantucket Shoals and Georges Bank. Thus there is a decreasing progression of wave energy from the North Atlantic, through the Gulf of Maine, up the Bay of Fundy to the very protected upper Bay. The rough estimates made indicate that wave heights can on occasion be greater than the tide heights through much of the Gulf of Maine system, and are generally much greater in many areas.

Storm Surges

Large storms can have a significant impact on water levels (Fig. II-4). The surges have space scales similar to the driving system and time scales of several hours. They are of more concern in the western Gulf where they can have magnitudes greater than the tides. In the upper Bay of Fundy they can still cause problems when storm surges arrive at high water.



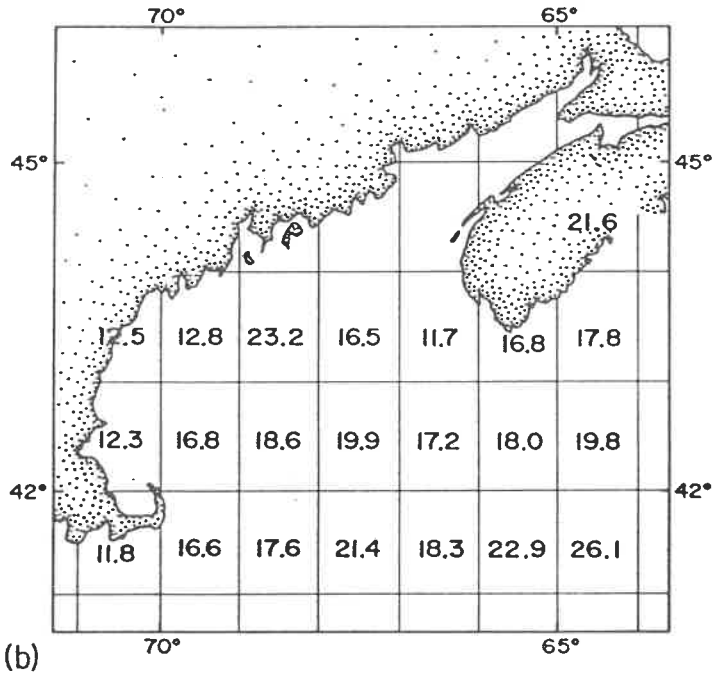


Fig. II-3. The one year (a) and the 100 year (b) significant wave height (in metres) in the Gulf of Maine (cf. 4). Wave energy decreases near the coast from these open sea values.

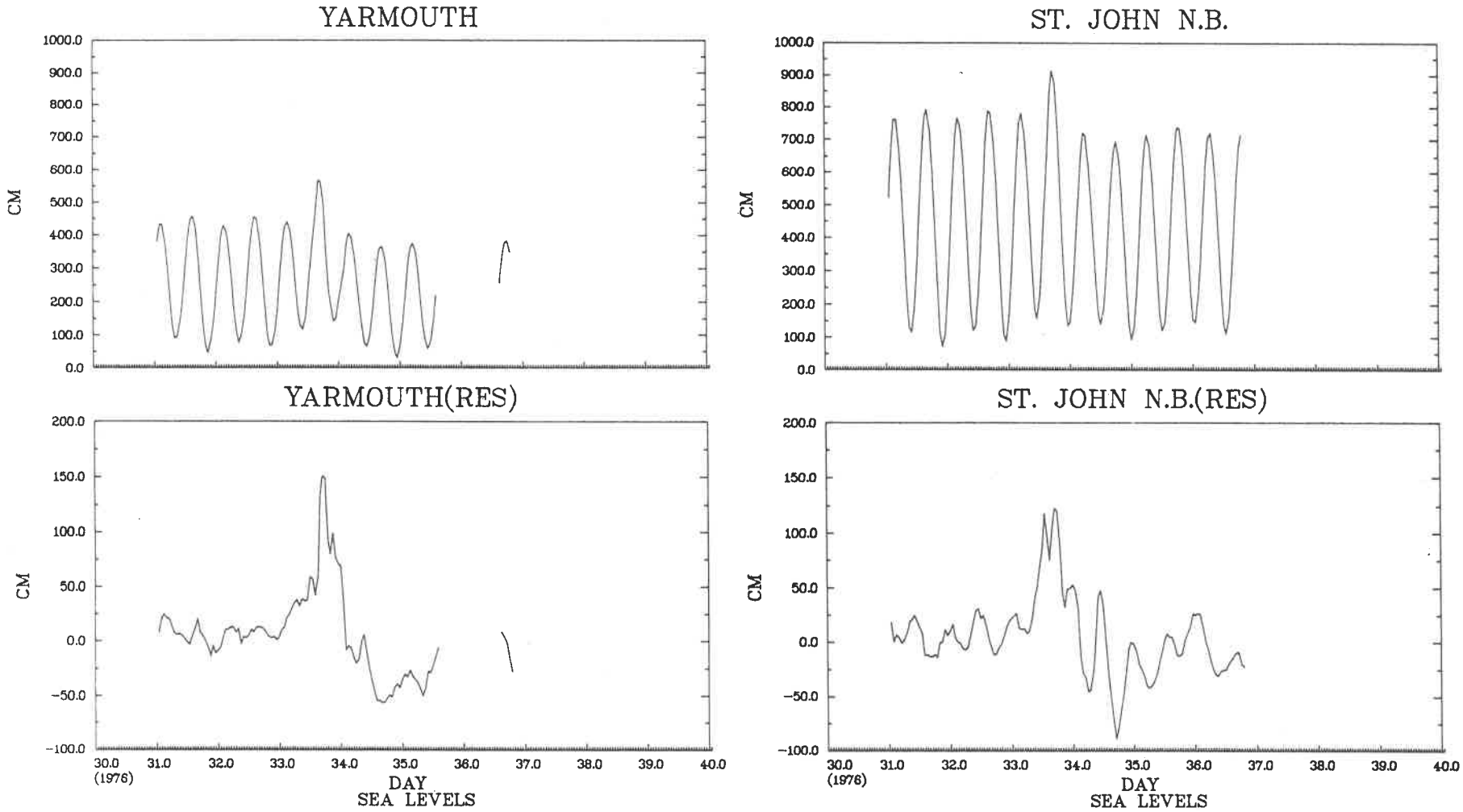


Fig. II-4. The hourly observed tidal levels at Yarmouth and Saint John and the residuals calculated by subtracting the predicted tides for Jan. 31 - Feb. 6. The large residuals are the result of the storm surge caused by the Feb. 2, Groundhog Day Storm. Damage at the head of the Bay was increased because the surge coincided with high tide.

Seasonal and Climatic Winds

Steady winds can have a small, but noticeable effect on sea level. In the Fundy-Maine system, components persisting for more than a few days result in steady current and elevation patterns. Saunders'(12) analysis of wind stress shows seasonal differences that would cause similar variations in sea level. Wright *et al.*(16) show that the magnitude of these variations could be 5 or 6 cm along the Maine coast (Fig. II-5). Longer term climatic variations are known to exist(15). Noble and Butman(11), looking at wind-induced sea level variations along Eastern North America, have found good correlations between coastal sea level and wind stress with periods between 60 and 600 hours.

TSUNAMIS

In the Canadian classification, the Atlantic provinces are rated as being moderately active seismically, with fault lines delineated down the middle of the Bay of Fundy and its branches. The 1929 earthquake off Newfoundland is known to have given rise to a significant tsunami with flooding reported(10) on the south shore of Newfoundland due to a wave over 30 m high in Burin Inlet. Recent earthquakes in New Brunswick have been small and no water level effects have been reported but tsunamis cannot be dismissed as being unimportant. Tsunamis are deep water waves with periods from 5 to 90 minutes. The most damaging ones are usually attributed to a combination of large earthquakes, usually but not always centered under the sea, and local resonance effects.

TIDES

Semidiurnal and Diurnal Tides

The Fundy-Maine system has a natural period of about 13.3 hours(3) and is in near resonance with the semidiurnal tides. This gives rise to an amplification of the M_2 tide from 1 m range at the edge of the continental shelf to over 12 m in upper Minas Basin (Fig. II-6). Combined with other constituents a tidal range of close to 17 m has been observed - the highest tides in the world. All of the semidiurnal constituents are amplified in the system, but M_2 is the largest and can be considered the mean tide. The diurnal constituents do not vary much throughout Fundy-Maine as there is little resonant amplification at periods as large as 24 hours. The largest diurnals have amplitudes between 10 and 20 cm.

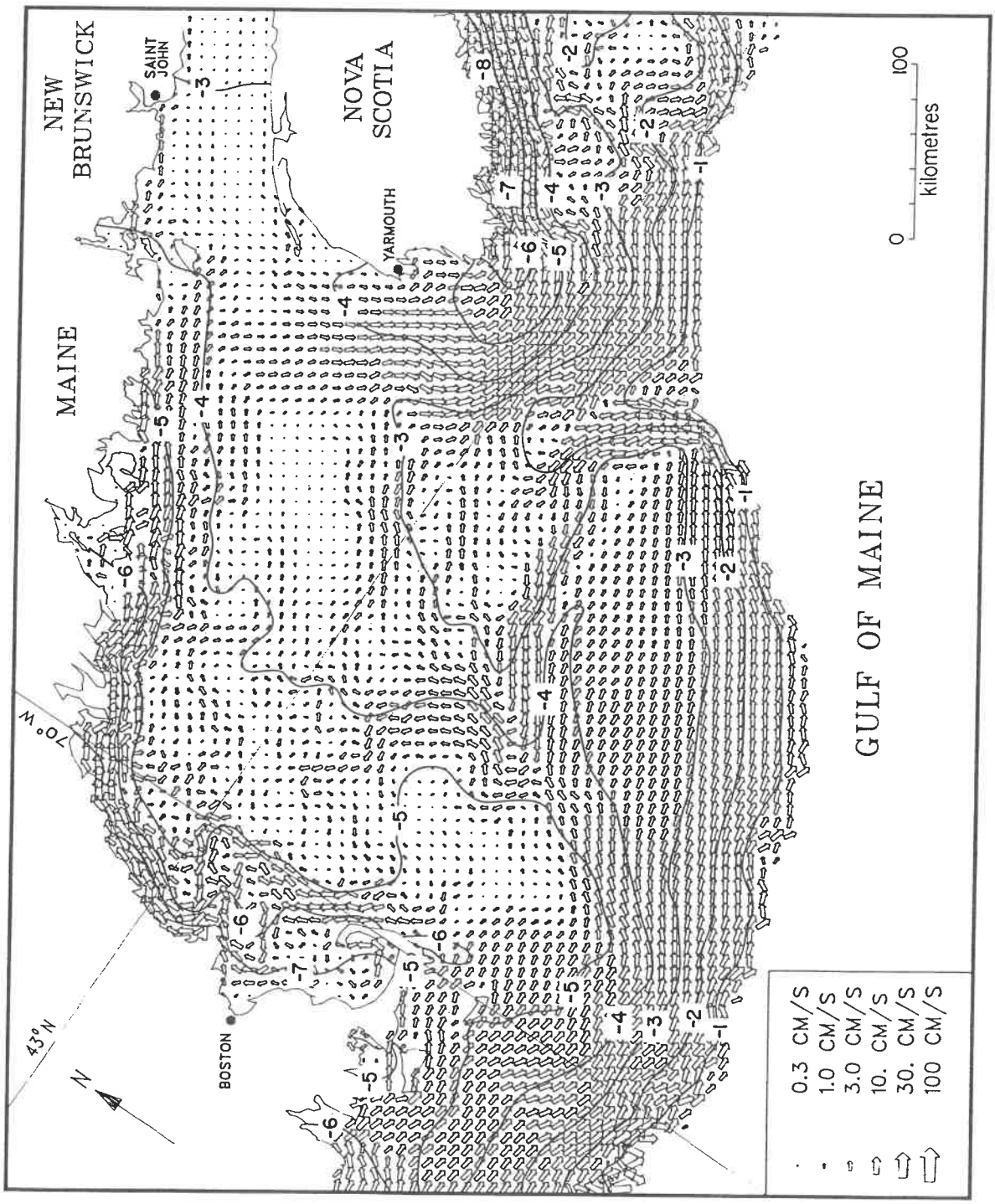


Fig. II-5. The currents and resultant set down in the Gulf of Maine from a 1 dyne cm^{-2} wind from the southwest(16).

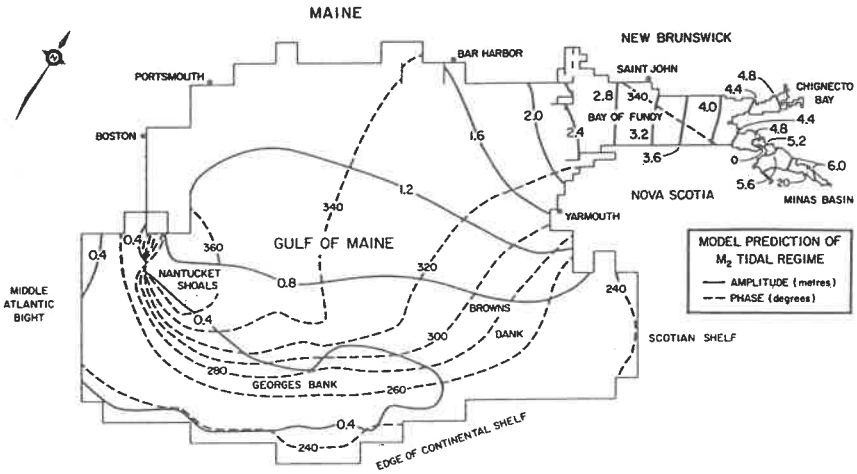


Fig. II-6. The amplitude and phase of the M_2 tide as calculated from a numerical model(5).

Periods Longer Than Diurnal

The tidal constituents with periods greater than the diurnals and up to one year are very small and are usually significant only when annual or seasonal climate and fresh water effects are large. Variation of the semi-diurnal and diurnal tides at these periods is due to the individual constituents moving in and out of phase on fortnightly, monthly, semiannual and annual time scales.

When analyzing tidal records, allowance is made for an amplitude variation with period 18.6 years - caused by variations in the declination of the moon's orbit. Theoretically, the amplitude of the M_2 tide varies by $\pm 3.7\%$ over the 18.6 year period. Ku *et al.*(9) found agreement in simple theory, observation and numerical model results, that resonance and friction effects reduce this amplification to about 2.4% in the Fundy-Maine system. Since the analysis and prediction of tides by Canadians and Americans assumes the 3.7% value, the predictions would be wrong by as much as 2.5% (about 8 cm at Saint John) in M_2 depending on the year of analysis and the year of prediction. Some of the other semidiurnals might also be affected. The diurnals seem to follow the theoretical pattern since they are not influenced by Fundy-Maine resonance.

Changes Due to Tidal Power

Greenberg(5) has calculated changes that might occur in the Fundy-Maine tidal regime if tidal barriers were to be constructed at the head of the Bay. These changes were related to resonance and frictional properties of the system. Tides would decrease near the barrier and increase away from the barrier by as much as 22 cm in M_2 tidal amplitude (Fig. II-7). The changes would be felt throughout the Bay of Fundy and Gulf of Maine and would diminish as one moves out of the Gulf by Cape Cod and around

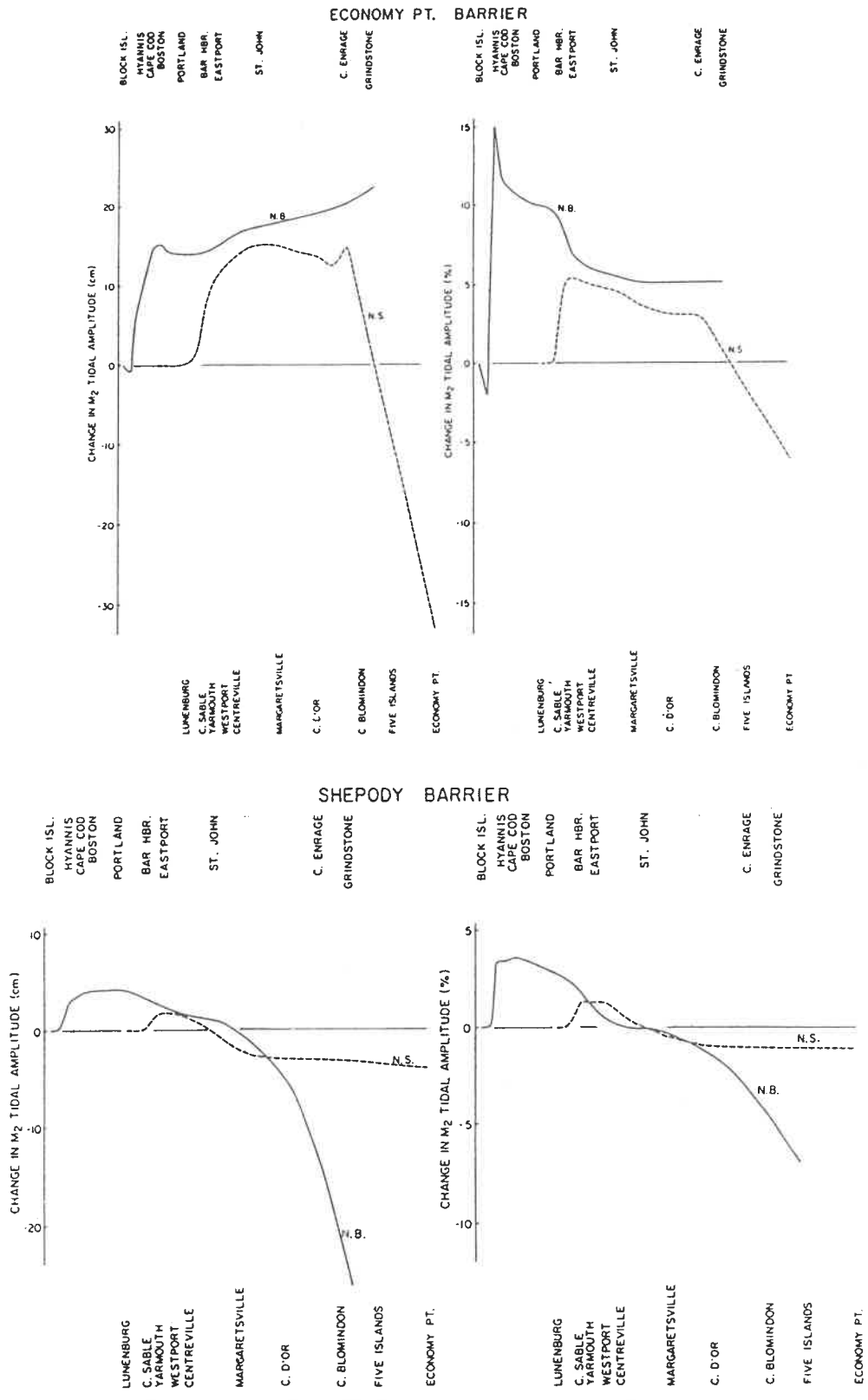


Fig. II-7. The change in M_2 tidal amplitude resulting from the constructing of tidal power barriers(8).

southwest Nova Scotia. In the reservoir behind the barrier more dramatic effects would be noticed. The tides would be very much reduced, and mean level would depend on the type of operation. More detailed descriptions of the physical oceanography and changes due to tidal power can be found elsewhere(7,8). A further investigation of tidal effects has been carried out by DeWolfe (Chapter III this volume) using the same model to look at some different aspects of barrier operation and installation.

Tides and Mean Sea Level

A change in mean sea level would also bring about a change in the tide. Scott and Greenberg(13) have investigated the problem of changing tide with changing sea level and have found that the principal factor determining the magnitude of the tides is the depth of water on the continental shelf seaward of a line from Cape Cod to Yarmouth. The detail of the tidal regime (the last few per cent) will depend on local depth changes, frictional and resonance effects, but the blocking effect of Georges Bank seems to be the most important factor. Tides in the inner Gulf of Maine are predicted to increase by about 1.7% for every one meter increase in depth on the outer shelf. Thus if the predicted sea level rise of 30 cm per century(1) is accurate, a further increase of high water by about 0.5% per century can also be expected.

CONCLUDING REMARKS

1. The surface defined by the mean sea level at different points is not necessarily level (in a gravitational sense) and may vary in time depending on the averaging period.

2. The large tides in the Bay of Fundy and Gulf of Maine are not the only source of variation in sea level. Storm surges and waves can dominate in many areas, and other processes can still be significant.

3. In determining extremes for flood forecasting and designing shore defence systems it should be remembered that the individual processes are not always independent. The coincidence of a deep low pressure raising static water levels, a storm surge and high surface waves, is certainly a real possibility. Storm surges and tides can interact, modifying both from the form they would take if considered independently.

4. Although most of the interest in sea level variation is addressed to the problems associated with exceeding certain levels, it should be remembered that there are processes that are bound to lower water level. (See pp. 123-125 this volume.) The above phenomena apply equally to these.

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III. AN UPDATE ON THE EFFECTS OF TIDAL POWER DEVELOPMENT ON THE TIDAL REGIME OF THE BAY OF FUNDY AND THE GULF OF MAINE

David L. DeWolfe

BACKGROUND AND INTRODUCTION

It has long been known that the installation and operation of a tidal power plant in the upper reaches of the Bay of Fundy will cause changes to the tidal regime throughout the Bay of Fundy and the Gulf of Maine. The most recent detailed work by Greenberg(4) shows the magnitude of these changes.

Since Greenberg's work, new strategies have been developed in the proposed configuration of tidal power plants(5). These recent developments were incorporated into a new specification of a barrier and the Greenberg model was then rerun to provide insight into the effects of different configurations on the tidal regime of the Fundy-Maine system.

It is known that the changes to the tidal regime are related to the volume of flow through the barrier. A major purpose of this work was therefore to determine the relationship between the permeability of the barrier and the magnitude of the changes to the tidal regime throughout the Bay of Fundy and Gulf of Maine. Relevant experiments for both the Cumberland Basin (A8) and Economy Point-Tennycape (B9) sites are described in this paper.

The generally accepted figures for the change in the tidal regime in the Bay of Fundy and Gulf of Maine have been based on the results of the Greenberg model using the M_2 tidal constituent only. However, in order to get a realistic assessment of barrier-induced changes, as well as their frequency distributions, it is necessary to calculate the changes that result from the operation of the tidal power plant over a lunar month. This allows the neap-spring cycle and the perigee-apogee cycle to be modelled and the changes to the tidal regime can then be investigated in a statistical manner. This work is also described in this paper.

THE MODEL

Introduction

The numerical model that forms the basis for this work is the finite-difference M_2 tidal model described by Greenberg(4). It covers the entire Bay of Fundy and Gulf of Maine out to the continental shelf, as well as a portion of the Scotian Shelf and the area south of Cape Cod. The model grid is shown in Fig. III-1.

The equations of motion and continuity used in this model are in their non-linear form and include Coriolis acceleration, real depth and quadratic friction. The advective terms in the equations of motion are commonly excluded in numerical tidal modelling. In Greenberg(4) they were included for Minas Channel and Minas Basin because they have an important influence where strong tidal currents change direction rapidly within confined areas. Greenberg(4) has since revised the model to include the advective terms in the entire sea area covered by the model, and this revised version is used in this work.

Calibration

The earlier results(3) for both the natural regime and the tidal regime modified by a barrier at B9 were duplicated. Since this earlier work computed the advective terms in Minas Channel and Minas Basin only, the advective terms in the present version had to be "switched off" and the friction readjusted in order to get a close agreement with the previous work. This was done for both the natural regime and for a B9-modified regime until the results of Greenberg(3) were satisfactorily duplicated.

Once verification was complete, the advective terms for the entire area were "switched on" and the friction readjusted to produce a benchmark run of the natural tidal regime to serve as the basis for measuring all barrier-induced changes to the tidal regime.

Updating the Barrier Specification

The previous work used a relatively simple specification of the flow through a turbine, which was assumed to have the same flow characteristics as a sluice. This did not allow for complications of flow through an optimized turbine. In addition, the specification of the number of sluices and turbines in the barriers has been updated. To allow for these changes, new barrier subroutines were developed and incorporated into the model for both the A8 and B9 barriers. The layouts are as follows:

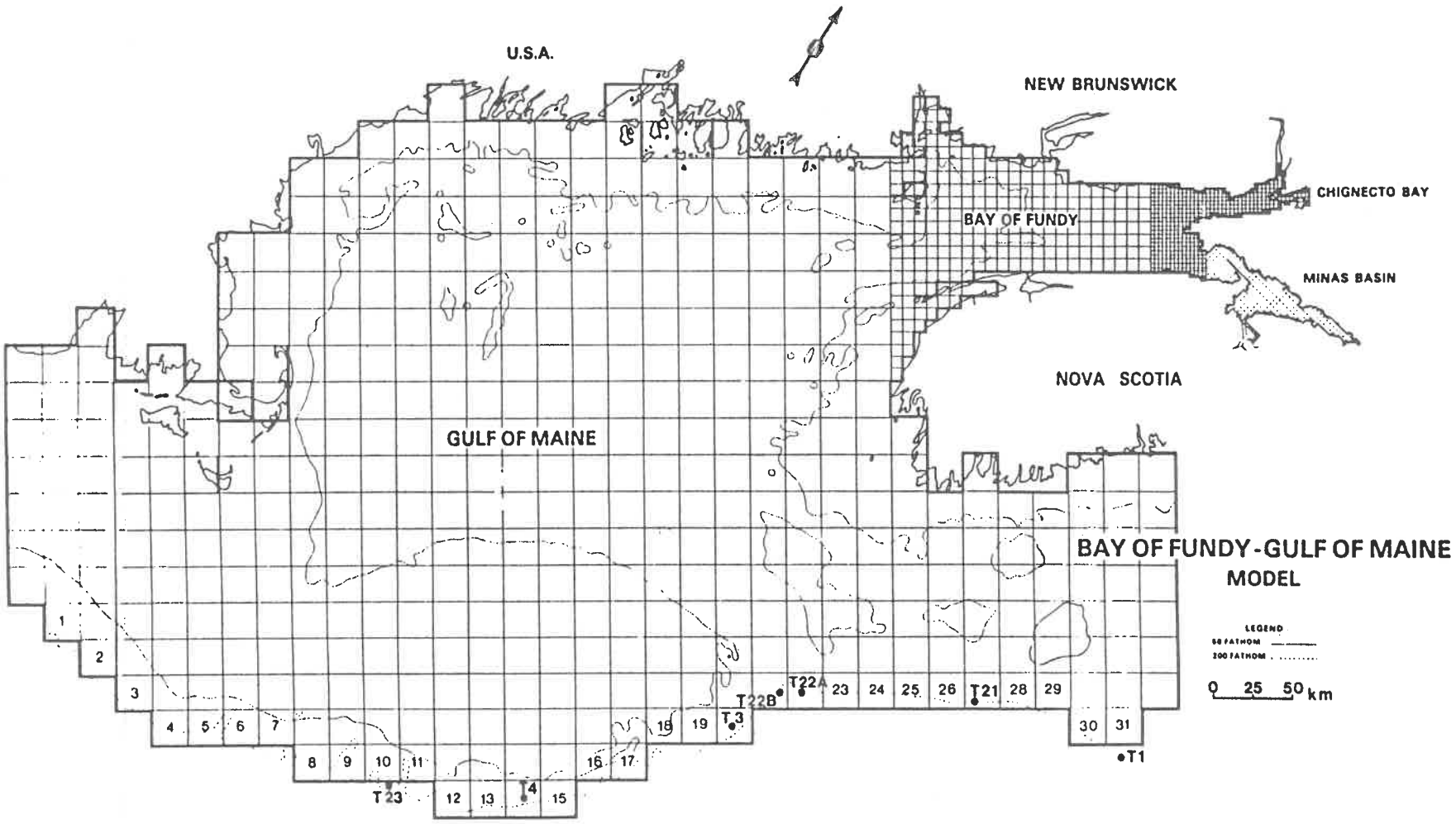


Fig. III-1. The grid outline for the latest version of the Bay of Fundy - Gulf of Maine numerical model (from Greenberg 1979).

A8 37 turbines, 35 operating, 24 sluices
B9 128 turbines, 120 operating, 97.5 sluices

The new barriers simulate a greater installed capacity as well as more physically realistic turbine flow.

VARIATION OF THE BARRIER PERMEABILITY

Introduction

Before experimenting with changing the permeability of a barrier, the model was run to duplicate the natural tidal regime. The amplitudes and phases of the M_2 tide for this run were recorded for all the grids in the model, for both elevation and the U and V components of the M_2 current. This calculation became the "benchmark" from which to measure the barrier-induced changes to the tidal regime.

The objective was to assess changes in the tidal regime throughout the Bay of Fundy and Gulf of Maine that would result from changing the permeability of the barrier. A run was made with the optimized turbine barriers for both A8 and B9. The experiment at A8 consisted of calculating the tidal regime with normal barrier operation using the optimized turbines and a run in which the sluices were left open. In the case of B9 there were four experiments:

1) normal operation using the optimized turbines
2) vary the starting and ending heads
3) vary the sluice capacity
4) leave the sluices open and vary the sluice capacity.

The results of these experiments for both A8 and B9 are shown in Tables III-1 and III-2.

Results and Discussion

The tidal regime resulting from the "new" barrage with normal operation at B9 and A8 was almost identical to that calculated by Greenberg(4). The results of all of these experiments are shown in Tables III-1 and III-2 and are grouped according to the similarity of the experiment. It appeared that the phase of the system was essentially impossible to change with a barrier at either B9 or A8 and that only the amplitudes of the M_2 tide could be modified by operation of the barrage.

There appears to be a predictable relationship between the operation of the barriers at both A8 and B9 and the resulting changes to the tidal regime in the Bay of Fundy and Gulf of Maine. It could be concluded that it is possible to modify the changes to the tidal regime in the Bay of Fundy and Gulf of Maine by varying the operation of the barrage. This

Table III-1. Amplitude changes of the M_2 tide at selected locations in the Bay of Fundy/Gulf of Maine system that result from the various experiments listed at the bottom of the table.

EXP	Headpond (cm)	Barrier Seaward (cm)	St. John (cm)	Yarmouth (cm)	Bar Hr. (cm)	Boston (cm)
1(a)	-407	-37	17	8	13	13
(b)	-395	-38	16	8	12	12
(c)	-391	-35	16	7	12	12
2(a)	-378	-41	16	8	12	12
(b)	-410	-36	18	8	13	13
3	-188	-71	5	5	7	8
4(a)	-77	-31	2	2	3	3
(b)	-156	-42	5	4	5	6
(c)	-331	-40	14	7	11	11
5(a)	-396	-4	12	6	10	12
(b)	-386	-16	13	7	11	11
(c)	-385	-17	14	7	10	11
(d)	-419	-27	15	7	11	11
6(a)	-259	-31	0	1	1	2
(b)	-53	-15	-1	0	0	0

EXPERIMENT

1. B9 Variation of starting and ending heads.
   (a) Starting head 625 cm, end head 187 cm
   (b) Starting head 450 cm, end head 125 cm
   (c) Starting head 312 cm, end head 187 cm

2. (a) B9 optimized turbines, normal operation.
   (b) B9 optimized turbines, normal operation sluices = 1/3 normal capacity.

3. B9 optimized turbines, all flows doubled.

4. (a) B9 optimized turbines, all sluices left open.
   (b) B9 optimized turbines, 2/3 sluices left open.
   (c) B9 optimized turbines, 1/3 sluices left open.

5. (a) B9, sluices opened at 2 hours before low water.
   (b) B9, sluices opened at 1 hour before low water.
   (c) B9, sluices opened at low water.
   (d) B9, sluices opened 1 hour after low water.

6. (a) A8 optimized turbines, normal operation.
   (b) A8 optimized turbines, all sluices left open.

Table III-2. Phase changes of the M2 tide at selected locations in the Bay of Fundy/Gulf of Maine as a result of the experiments listed at the bottom of the table. Phase changes in degrees.

EXP	Headpond (deg)	Barrier Seaward (deg)	St. John (deg)	Yarmouth (deg)	Bar Hr. (deg)	Boston (deg)
1(a)	55	-16	-2	0	0	2
(b)	51	-15	-2	0	0	2
(c)	48	-15	-2	0	0	2
2(a)	51	-15	-2	0	0	2
(b)	59	-17	-2	0	0	2
3	35	-7	-3	-1	-1	0
4(a)	15	-4	-1	-1	-1	0
(b)	25	-7	-2	-1	-1	0
(c)	42	-14	-2	0	0	2
5(a)	51	-15	-2	0	-1	1
(b)	60	-15	-2	0	0	1
(c)	66	-15	-2	0	0	1
(d)	65	-17	-2	0	0	1
6(a)	62	-3	-1	-1	-1	0
(b)	22	0	0	0	0	0

EXPERIMENT

1. B9 1976 version. Variation of starting and ending heads.
   (a) Starting head 625 cm, end head 187 cm
   (b) Starting head 450 cm, end head 125 cm
   (c) Starting head 312 cm, end head 187 cm

2. (a) B9 optimized turbines, normal operation.
   (b) B9 optimized turbines, normal operation; sluices = 1/3 normal capacity.

3. B9 optimized turbines, all flows doubled.

4. (a) B9 optimized turbines, all sluices left open.
   (b) B9 optimized turbines, 2/3 sluices left open.
   (c) B9 optimized turbines, 1/3 sluices left open.

5. (a) B9, sluices opened at 2 hours before low water.
   (b) B9, sluices opened at 1 hour before low water.
   (c) B9, sluices opened at low water.
   (d) B9, sluices opened 1 hour after low water.

6. (a) A8 optimized turbines, normal operation.
   (b) A8 optimized turbines, all sluices left open.

is an important result because it shows that the operators of a barrage would have some measure of control over the far field changes resulting from a tidal barrage. At times of extreme water levels such as those that occur during storm surges and other high tide events, damage due to flooding could be minimized by simply opening the sluices at the plant and leaving them open until the danger is past.

MODELLING THE TIDES FOR A LUNAR MONTH

Introduction

The modelling discussed so far used only the M_2 tidal constituent, which more or less represents the mean tide in the Bay of Fundy. Other constituents are responsible for variations such as the neap-spring cycle, the perigee-apogee cycle, and the diurnal inequalities. These cycles can be effectively reproduced by six principal tidal constituents, O_1, K_1, N_2, M_2, L_2, and S_2. A much more realistic tide for the Bay of Fundy and Gulf of Maine could be simulated if the model is run for a period of a lunar month with the above constituents as inputs. To do this, the elevation specified at the open boundary had to be altered to reflect that which would result from using the above constituents rather than M_2 alone.

The model had to be re-calibrated because the introduction of additional constituents necessitates the reduction of friction throughout the model area. The model was started from a previous calculation with the M_2 constituent which had an elevation field very close to what was required for the start of the long runs, and then run for a period of 33 days with a time-step of 30 sec. for both the natural tidal regime and a B9-modified regime. The first four days were discarded because of the necessity of the model to "warm-up", and the remaining 29 days were saved as a set of hourly elevations at 14 locations around the system.

Analysis

The analysis of the model output at the 14 locations followed the same path as if these were real tidal data collected in the field. The first step was to perform a least squares harmonic analysis on the data for the amplitudes and phases of the principal harmonic constituents. The nodal factor (18.6 yr. nodal cycle) was specified to be 1.0 in the analyses. This allowed comparisons to be made with other years with other values of the nodal cycle.

The tidal constituents themselves were then analyzed to determine the lunitidal intervals and ratios, which is the same method used to calculate tidal datum planes in Canada -- being higher high water large tides (HHWLT), lower low water

large tides (LLWLT), higher high water and lower low water mean tides (HHWMT and LLWMT), and lower low water mean tide and the higher low water mean tide (LLWMT and HLWMT). These figures permit the calculation of the spring tide range, neap tide range, the mean tide range as well as chart datum.

The constituents calculated for both the natural regime and the B9 modified tidal regime, were then used to predict the high and low tide for a year at each of the output locations. This allowed calculation of the frequency distribution of the barrier induced changes to the high and low water levels over the Bay of Fundy and Gulf of Maine. It also allowed investigation of the effects of nodal modulation on these changes. Predictions were made for three different years -- 1978 when the semi-diurnal nodal modulation is maximum, 1987 when it is minimum, and 1992 when it is equal to 1.

Results

The amplitudes and phases of the six harmonic constituents for the barrier modified tidal regime, together with their changes from the natural regime, are listed in Tables III-3 and III-4. The phases shown in Table III-4 have been corrected to Atlantic Standard Time, (GMT-4 hr).

The mean tide and large tide ranges for locations around the Bay of Fundy and Gulf of Maine were calculated from the harmonic constituents, and are shown in Table III-5. Mean tides are under the headings "observed", "natural" and "B9". "Observed" values are extracted from tide tables and other appropriate publications such as the Marine Environment Data Service "blue file". "Natural" values are calculated from the model. The quality of the calibration of the model at the various locations around the Bay of Fundy and Gulf of Maine can be seen by comparing the "observed" with the "natural" values. The differences are generally within 10 cm at Providence, Boston, Saint John, Cape Enrage, Grindstone and Cap d'Or. For other locations such as St. Andrews and Yarmouth, the differences between the "observed" and "natural" mean tide are somewhat larger. In general, the calibration of the model for the 29 day runs is considered good.

The changes to the values of mean tide and large tide were determined from the lunitidal calculations for both the natural and the B9 modified tidal regime and are shown in Table III-6. In general, changes to the high water large tides are greater than to the high water mean tides. Similarly, both the low water large tides and the low water mean tides are lower than without the barrier. The low water large tide is lower than the low water mean tide. The exception to this is the area just seaward of the barrier where the M_2 tide is decreased. At Five Islands for example, the barrier-modified high water

Table III-3. The amplitudes of the principal tidal constituents for the B9-modified tidal regime, obtained by harmonic analysis of the model output. The change in amplitude from the natural regime is tabulated in the 'change' row.

	O_1 (cm)	K_1 (cm)	N_2 (cm)	M_2 (cm)	L_2 (cm)	S_2 (cm)
Georges Bank	7.4	7.9	8.9	42.5	2.2	5.3
change	0	0	-0.1	1.5	0	-0.5
Providence	6.1	7.2	11.7	58.8	2.4	11.0
change	0	-0.1	0	-0.4	0.1	0
Boston	10.9	12.0	29.6	152.1	4.3	23.2
change	-0.1	0	1.3	12.5	-0.5	0.8
Portland	10.9	12.1	29.3	153.4	4.3	24.0
change	-0.1	0	1.3	12.1	-0.5	1.0
Bar Harbour	10.8	12.4	33.2	178.3	4.9	27.3
change	0	0	1.5	12.8	-0.7	1.2
St. Andrews	11.8	13.8	52.8	300.0	7.2	49.0
change	-0.2	-0.1	2.2	17.0	0.1	2.7
Saint John	11.7	13.8	57.3	323.0	7.9	53.1
change	-0.1	-0.1	2.6	17.2	-1.3	2.9
Cape Enrage	12.3	14.8	80.3	463.6	11.5	78.5
change	-0.2	-0.1	3.6	18.5	-1.6	4.4
Grindstone	12.5	14.6	85.7	501.2	12.2	85.4
change	-0.1	-0.6	3.7	20.1	-1.3	4.6
Cape D'Or	12.4	14.8	78.3	453.4	11.1	76.7
change	-0.2	-0.2	3.4	14.4	-2.8	1.8
Five Islands	12.7	15.5	92.8	548.9	14.6	94.0
change	-0.6	-0.2	2.5	-15.5	-7.4	2.1
Cobequid Bay	14.5	9.6	15.3	214.0	32.2	20.6
change	1.0	-6.2	-82.5	-404.3	6.8	-80.7
Yarmouth	10.4	12.3	30.0	156.5	4.2	25.6
change	-0.1	-0.1	0.6	7.0	-0.4	0.3

Table III-4. The phases of the principal tidal constituents for the B9-modified tidal regime, obtained by harmonic analysis of the model output. The change in phase from the natural regime is tabulated in the 'change' rows.

	O_1 (deg)	K_1 (deg)	N_2 (deg)	M_2 (deg)	L_2 (deg)	S_2 (deg)
Georges Bank	128	110	226	243	211	268
change	4	0	3	4	-11	5
Providence	143	112	241	253	210	272
change	0	1	0	0	1	0
Boston	133	147	331	357	12	33
change	0	0	3	2	-21	7
Portland	127	142	322	349	7	24
change	0	0	3	1	-23	6
Bar Harbour	118	135	308	337	13	11
change	0	0	2	0	-21	4
St. Andrews	132	144	319	348	329	25
change	0	0	1	-1	-22	3
Saint John	117	136	313	340	329	19
change	-1	0	-1	-2	-22	1
Cape Enrage	116	133	311	346	327	28
change	-1	-1	-2	-4	-26	0
Grindstone	119	134	320	345	327	32
change	-2	-2	-2	-3	-26	0
Cape D'Or	115	136	316	340	357	19
change	-1	-1	-4	-6	-23	-3
Five Islands	131	140	338	355	20	40
change	-3	-8	-14	-14	-17	-14
Cobequid Bay	232	252	43	65	69	118
change	96	98	51	52	65	51
Yarmouth	109	122	282	306	345	340
change	0	0	2	0	-19	4

Table III-5. Mean tide (MT) and Large tide (LT) ranges for locations around the Bay of Fundy and the Gulf of Maine listed for the observed values (obs), the no-barrier model (nat) and for the model with the B9 barrier (B9) inserted at Economy Point. The mean tide range is calculated according to the US convention for the stations in US waters, in order to make proper comparisons.

		MT obs (m)	MT nat (m)	MT B9 (m)	LT obs (m)	LT nat (m)	LT B9 (m)
Providence	RI	1.40	1.35	1.34	1.73	1.78	1.77
Boston	MA	2.90	2.88	3.13	3.35	4.10	4.43
Portland	ME	2.74	2.92	3.12	3.17	4.16	4.46
Bar Harb.	ME	3.20	3.40	3.65	3.69	4.81	5.12
St. Andrews	NB	5.97	6.12	6.44	8.03	8.03	8.44
Saint John	NB	6.54	6.55	6.89	8.74	8.64	9.08
Cape Enrage	NB	9.45	9.49	9.86	12.77	12.42	12.91
Grindstone	NB	10.20	10.27	10.65	13.80	13.45	13.94
Cape D'Or	NS	9.33	9.34	9.64	12.46	12.20	12.62
Five Is.	NS	11.56	11.92	11.64	15.40	15.43	15.27
Cobequid	NS	12.90	13.06	4.85	16.68	16.88	5.91
Yarmouth	NS	3.71	3.43	3.57	5.02	4.53	4.68
Lunenburg	NS	1.54	1.47	1.47	2.17	2.08	2.08
Georges Bank		1.00	0.98	1.01	1.33	1.30	1.33

Table III-6. Mean tide (MT) and Large tide (LT) changes as a result of the B9 barrage at Economy Point. The values have been calculated with respect to local datum and are shown for low water large tides, low water mean tides, high water mean tides and high water large tides.

Location		LW LT (m)	LW MT (m)	HW MT (m)	HW LT (m)
Providence	RI	.01	.00	-.01	.00
Boston	MA	-.14	-.14	.11	.16
Portland	ME	-.15	-.13	.11	.15
Bar Harb.	ME	-.18	-.13	.12	.13
St. Andrews	NB	-.22	-.16	.18	.19
Saint John	NB	-.25	-.17	.19	.19
Cape Enrage	NB	-.25	-.16	.22	.24
Grindstone	NB	-.25	-.16	.24	.24
Cape D'Or	NS	-.18	-.19	.12	.24
Five Is.	NS	.06	.04	-.23	-.11
Cobequid	NS	1.74	-.21	-5.73	-7.09
Yarmouth	NS	-.10	-.08	.06	.06
Lunenburg	NS	0	0	0	0
Georges Bank		-.01	-.01	.02	.02

large tides are 11 cm lower and the high water mean tides 23 cm lower. There is essentially no change at Providence and Georges Bank.

These figures represent the necessary adjustment to tide tables should a B9 barrier be constructed. The same lunitidal calculation shows the change in the arrival time of high and low tide due to a B9 barrier (Table III-7). Note that the headpond shows a lag of 1 hr 45 min. at high water and a lag of 2 hrs 1 min. at low water. Canadian and American methods of computing the mean tide range are different. In the U.S. the mean tide range is the difference between mean high water and mean low water, where mean high water is the average of two successive high waters and mean low water is the average of two successive low waters. In Canada, the mean tide range is the higher of the two high tides in the day, minus the lower of the two low tides in the day. It is therefore larger than the U.S. figure. For this paper, the U.S. method is used for U.S. locations, and the Canadian method for Canadian locations.

It is generally assumed that twice the M_2 amplitude should more or less equal the mean tide range. Twice the M_2 range was compared with both the American and Canadian mean tide ranges (Table III-8). In general, 2 * M_2 amplitude is roughly 3% less than the mean tide range calculated by the American method, but varies between 6 and 10% greater with the Canadian method. This is because the diurnal inequality is not averaged out in the Canadian calculation, and it thus becomes a larger percentage of the mean tide range for places where the tidal range is lower.

Table III-7. Time changes in high and low tide resulting from the B9 barrage at Economy Point. The time differences are computed from the lunitidal intervals resulting from an analysis of the output of the model 29 day runs.

		LW (min)	HW (min)
Providence	RI	0	0
Boston	MA	6	0
Portland	ME	4	2.5
Bar Harb.	ME	-1.5	2.5
St. Andrews	NB	-4.0	0
Saint John	NB	-7.0	-2.5
Cape Enrage	NB	-8.5	-6.5
Grindstone	NB	-8.5	-6.0
Cape D'Or	NS	-8.5	-13.5
Five Is.	NS	-26.0	-31.0
Cobequid	NS	121.0	105.0
Yarmouth	NS	0	2.5
Georges Bank		9.0	9.0

Table III-8. Comparison of mean tide range with twice the M_2 amplitude. The mean tide range is calculated by two methods. The American way, being mean high water minus mean low water, is labelled as MT(A). The Canadian way, being higher high water mean tides minus lower low water mean tides, is labelled MT(C).

		2*M2 (m)	MT(A) (m)	MT(C) (m)
Providence	RI	1.18	1.22	1.35
Boston	MA	2.78	2.87	3.10
Portland	ME	2.83	2.92	3.15
Bar Harb.	ME	3.31	3.40	3.63
St. Andrews	NB	5.66	5.86	6.12
Saint John	NB	6.12	6.28	6.55
Cape Enrage	NB	8.90	9.17	9.49
Grindstone	NB	9.62	9.95	10.27
Cape D'Or	NS	8.78	9.03	9.34
Five Is.	NS	11.29	11.59	11.92
Cobequid	NS	12.37	12.73	13.06
Yarmouth	NS	3.13	3.22	3.43
Lunenburg	NS	1.26	1.33	1.47
Georges Bank		0.82	0.85	0.98

Distribution of the Changes

In general, the changes to the tidal regime as a consequence of a tidal power plant have been assumed to be the value of the amplitude of M_2. This is clearly incorrect because of the variability of the tide (e.g. the perigee-apogee cycle, and the spring-neap cycle). Fig. III-2 shows the predicted high and low tide for Boston for 1992 and Fig. III-3 shows the changes to the predicted tides for Boston resulting from a B9 barrier for the same year. The maximum changes to the tidal regime occurred when the tides were at their maximum, and the minimum changes to the tidal regime occurred when the tides were at their minimum range. The changes to the high tide essentially mirrored the changes to the low tide. Therefore the frequency distributions shown for the changes in high tide are essentially identical to those that would have been shown for the changes in low tide. These differences for the high tides at Boston and Saint John are shown in Fig. III-4 as a set of bar charts.

Changes that result from a barrier at B9 can also be shown by a cumulative frequency distribution. Table III-9 shows this for all of the output locations for which the changes were positive (increased). At Five Islands and Cobequid in the headpond, the changes were negative and are not shown in this table. Table III-2 should be interpreted as follows: the change in the elevation of high water at Saint John was at least 7 cm all of the time, 18 or more cm 51% of the time, and 26 or more

Fig. III-2. The predicted high and low tides for Boston in 1992, using the constituents derived from the one month model run for the natural tidal regime.

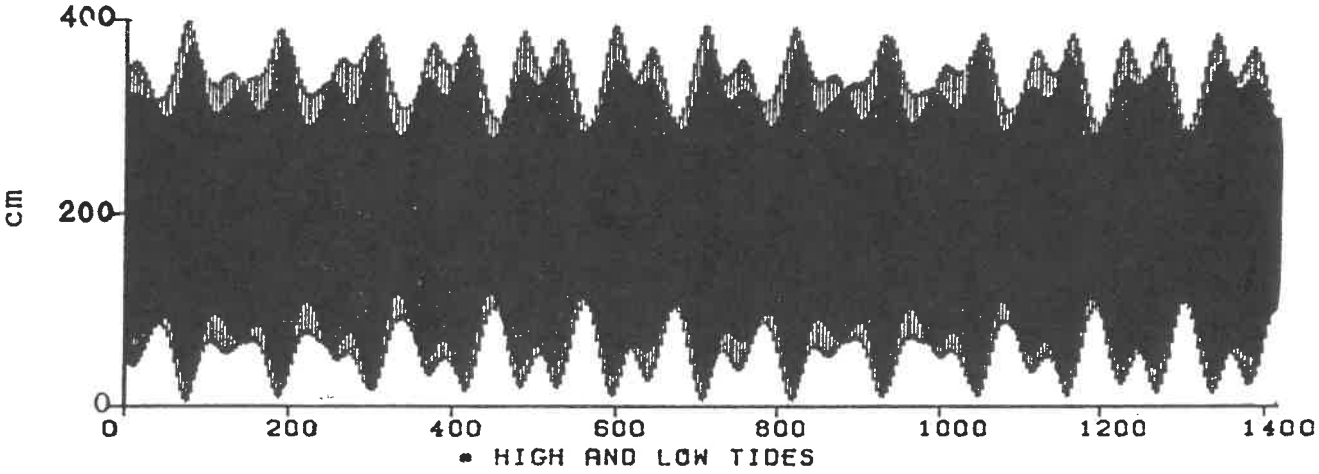
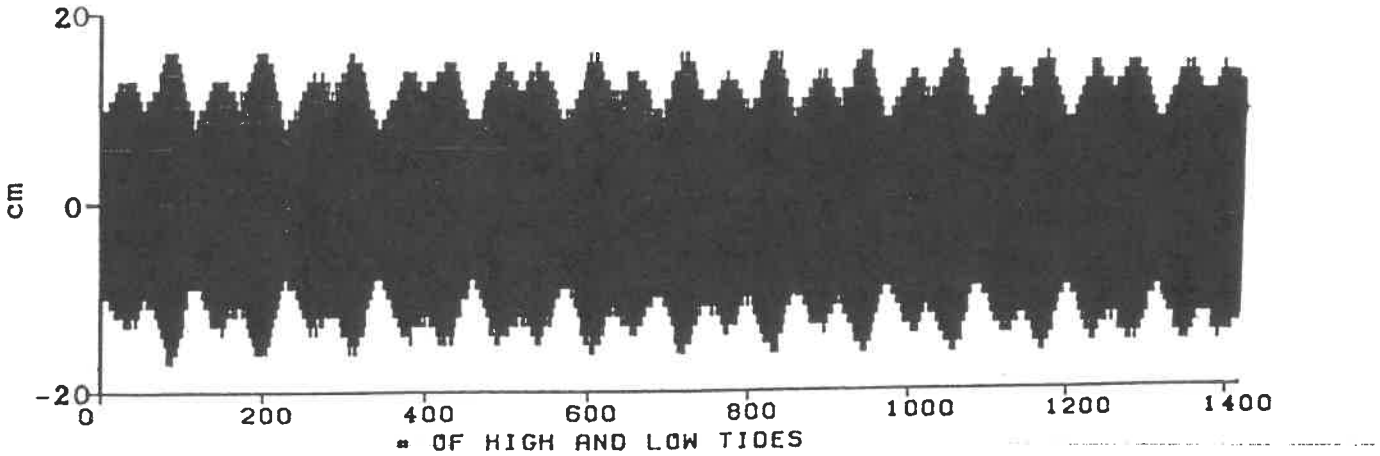
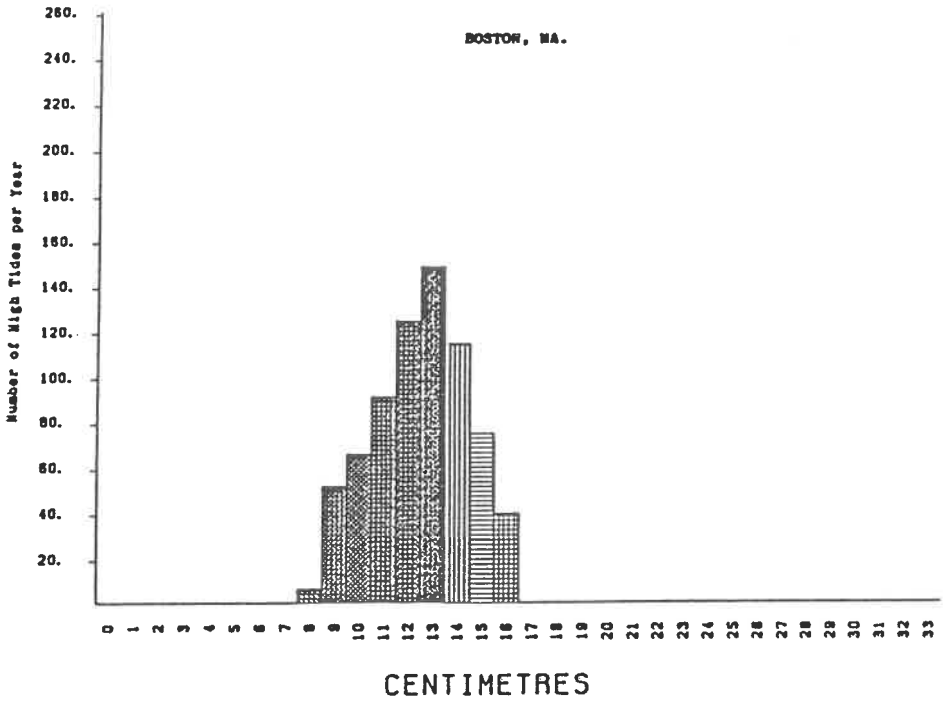


Fig. III-3. The changes to the tidal regime at Boston in 1992 obtained by subtracting the predicted high and low tides for the natural regime from the B9-modified regime.





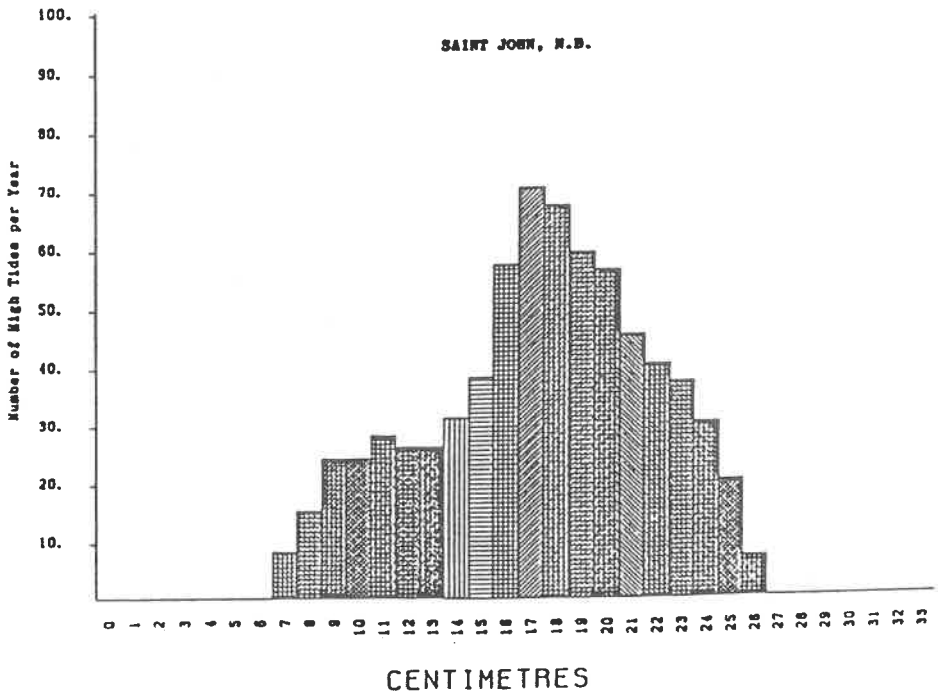


Fig. III-4. Frequency distribution of tidal range increments at Boston, MA and Saint John, N.B. following construction of a B9 barrage.

Table III-9. Cumulative frequency distribution of the changes to the tidal regime as a result of a barrier at Economy Point, (B9). These results were calculated by differencing one year of high tides for the natural regime and one year of the high tides resulting from the B9 modified tidal regime. They are expressed as the percent of the time at which the tide is at or above the tabulated change, and clearly show the effect of the neap-spring and perigee-apogee cycles on the tidal regime changes. The changes for low tide are virtually the mirror image of those for high tide.

[A]= Providence,RI [B]= Georges Bank [C]= Yarmouth, NS
[D]= Boston, MA [E]= Portland, ME [F]= Bar Harbour, ME
[G]= St. Andrews, NB [H]= St. John, NB [I]= Cape D'or, NS
[J]= Cape Enrage, NB [K]= Grindstone, NB

Change (cm)	[A] %	[B] %	[C] %	[D] %	[E] %	[F] %	[G] %	[H] %	[I] %	[J] %	[K] %
33										0	0
32										1	2
31										4	5
30										5	7
39										7	10
28										10	14
27										12	19
26								1		14	23
25								4		18	27
24							2	8		20	34
23							8	13	2	23	40
22							15	19	5	27	46
21							22	25	9	32	53
20							30	33	15	36	59
19							42	42	21	42	67
18							50	51	28	49	70
17						2	58	61	36	56	74
16				6	2	9	67	69	46	62	77
15				16	11	25	75	74	56	67	80
14				32	26	44	80	79	64	72	83
13				53	46	57	84	82	70	76	85
12				70	63	73	90	86	74	81	87
11				83	77	84	93	90	78	85	90
10				92	88	92	97	93	82	88	92
9			12	99	96	98	99	97	85	93	95
8			41	100	100	100	100	99	88	95	97
7			63					100	92	98	98
6			85						95	99	99
5			98						98	100	100
4			100						99		
3		5							100		
2		41									
1	25	82									
0	100	100									

cm 1% of the time. The previous assessment of changes at Boston stated simply that the elevation at Boston would increase by 15 cm. This present work indicates that the change at Boston will be 15 cm or more only 16% of the time, but will be at least 8 cm all of the time.

The Nodal Modulation

The inclination of the moon's orbit to the earth's equator varies between 18.3^{o} and 28.6^{o} over a period of 18.6 years. This causes the oceanic nodal tide which has a period of 18.61 years. The nodal modulation for the M_2 tide varies between +/- 2.5% to +/-3.7%. The modulation of the main lunar diurnal tides O_1 and K_1 are larger, being +/- 19% and +/-11% respectively, and out of phase with the M_2 modulation(1).

The nodal modulation has a measurable effect on the heights of high and low tides. The high and low tides for both Boston and Saint John were predicted for 1978 (nodal maximum), 1992 (nodal =1) and 1987 (nodal minimum). Table III-10 shows some effects of the nodal modulation on the tidal regime at Boston and Saint John. The average difference between the no-barrier tidal regime and the B9 tidal regime at Boston and Saint John did not change appreciably from one year to the next.

To look at the frequency distribution of the B9-induced changes in the tidal regime, the predicted tides for Boston and Saint John were calculated for both the barrier and the no-barrier case, and were then differenced. This was done for each of the three predictions of the nodal cycle and the results displayed as a cumulative frequency distribution (Table III-11). This shows that the B9-induced tidal change is not dependent on the value of the lunar nodal modulation for any particular year. Thus, although the B9 barrier would modify the tides, the particular value of the nodal cycle would not affect these changes in any significant way.

SUMMARY & CONCLUSIONS

The Greenberg model has been updated for this work in a number of important ways. The advective terms in the equations of motion have been extended to include the entire model area out to the continental shelf. The operational and structural specifications of the tidal barrage have been upgraded to reflect work done in the last few years(5). Recent specifications and calculations of flows through turbines optimized for maximum power output have also been incorporated.

As a result of updated experiments to determine the effects on the tidal regime of barrier permeability, it was found that the barrier-induced alteration of the natural tidal regime was more or less a predictable function of barrier permeability.

Table III-10. Effect of the 18.6 year nodal modulation on the changes to the tidal regime at Boston and Saint John as a result of a barrier at Economy Point (B9). The changes are expressed as a cumulative frequency distribution of one year's predicted high tide for 1978 (nodal maximum), 1992 (nodal = 1) and 1987 (nodal minimum). The changes for the low tides virtually mirror those for high tide.

Change	Boston			Saint John		
	1978	1992	1987	1978	1992	1987
(cm)	%	%	%	%	%	%
29				0		0
28				4		2
27				6		5
26				10	1	8
25				14	4	12
24				18	8	14
23				22	13	20
22				27	19	23
21				33	25	27
20				40	33	33
19				46	42	39
18	3		1	53	51	45
17	9		6	60	61	50
16	17	5	13	65	69	55
15	27	16	21	72	74	63
14	40	32	32	76	79	69
13	52	53	43	80	82	73
12	68	70	53	82	86	76
11	78	83	65	87	90	80
10	86	92	77	89	93	84
9	95	99	85	93	97	86
8	99	100	93	95	99	90
7	100		99	98	100	93
6			100	99		96
5				100		98
4						99
3						100
2						
1						
0						

Table III-11. Some effects of the nodal modulation on the tidal regime at Boston and Saint John. 1978 represents a year in which the nodal modulation is maximum, 1992 a year for which it is equal to 1 (average value) and 1987 is a year for which the nodal modulation is minimum.

	Boston			Saint John		
	1978	1992	1987	1978	1992	1987
maximum amplitude, natural regime (cm)	202	200	194	421	416	398
maximum amplitude, modified regime (cm)	216	214	208	449	441	424
mean change (cm)	12.7	12.5	11.9	17.7	17.3	16.4
standard deviation (cm)	2.6	1.9	2.9	5.8	4.5	6.2
largest change (cm)	18	16	18	29	26	29
smallest change (cm)	7	8	6	5	7	3

It is notable that when the sluices are left open over a whole tidal cycle the far-field changes in the tidal regime were substantially reduced.

Simulation of both the natural and B9-modified tidal regimes in the Bay of Fundy and Gulf of Maine for a lunar cycle shows the maximum change to the tidal regime that will take place as well as the frequency distributions of the changes throughout the year. The effects of the 18.6 year nodal modulation on the far-field barrier-induced changes have been determined to be negligible.

ACKNOWLEDGEMENTS

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I thank David Greenberg for much helpful discussion.

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IV. A BRIEF REVIEW OF PRIMARY PRODUCTION IN THE GULF OF MAINE AND THE BAY OF FUNDY

Donald C. Gordon, Jr.

INTRODUCTION

The Gulf of Maine and Bay of Fundy (Fig. IV-1) are dynamic environments subject to continuous change. Local sea level has been rising for about the past 7000 years due to crustal subsidence and continues today at a rate estimated to be 13-21 cm century^{-1}(23). Sea level is also increasing at an unknown rate because of global warming, brought about by the 'greenhouse effect,' which is melting polar ice (cf. Titus & Wells Ch. 1). As the depth over Georges Bank increases, so does the tidal amplitude, at a rate of about 4 cm century^{-1}(23). On top of all this, tidal power development in the upper reaches of the Bay of Fundy could also increase tidal range over most of the Gulf of Maine and Bay of Fundy by as much as 30 cm in just a few years. The net effect of all these processes on mean sea level, mean high water and mean low water is summarized in Fig. IV-2.

Such changes in water levels, and the corresponding alterations in tidal currents, influence a wide variety of ecological processes in the Gulf of Maine and Bay of Fundy. This paper examines in a very preliminary fashion the likely impacts on primary production by phytoplankton, macroalgae, saltmarshes and sediment microalgae. Because of time constraints and the lack of data in some instances, this is by no means an exhaustive review but it should illustrate the general level of our present understanding. Hopefully this paper will also stimulate some of the research necessary to fill the many data gaps.

PRESENT PRIMARY PRODUCTION PATTERNS

Phytoplankton

Phytoplankton are most abundant in the well-mixed frontal areas over Nantucket Shoals and Georges Bank, off southwest Nova Scotia, at the mouth of the Bay of Fundy and along the Maine coast. Abundance in the centre of the Gulf of Maine is relatively low(30). Concentrations seem to be especially high in

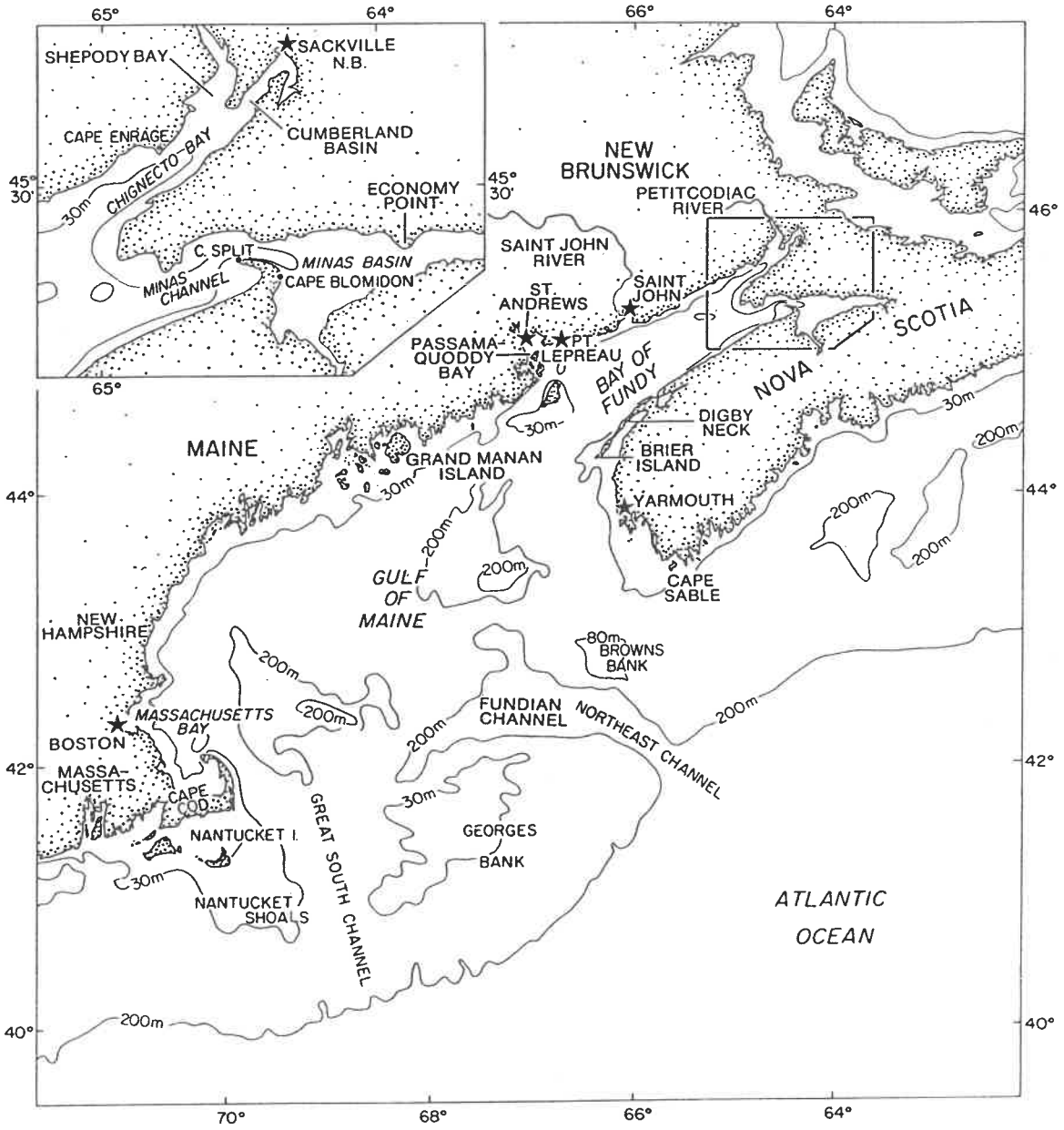

Fig. IV-1. Location Map for the Bay of Fundy and Gulf of Maine

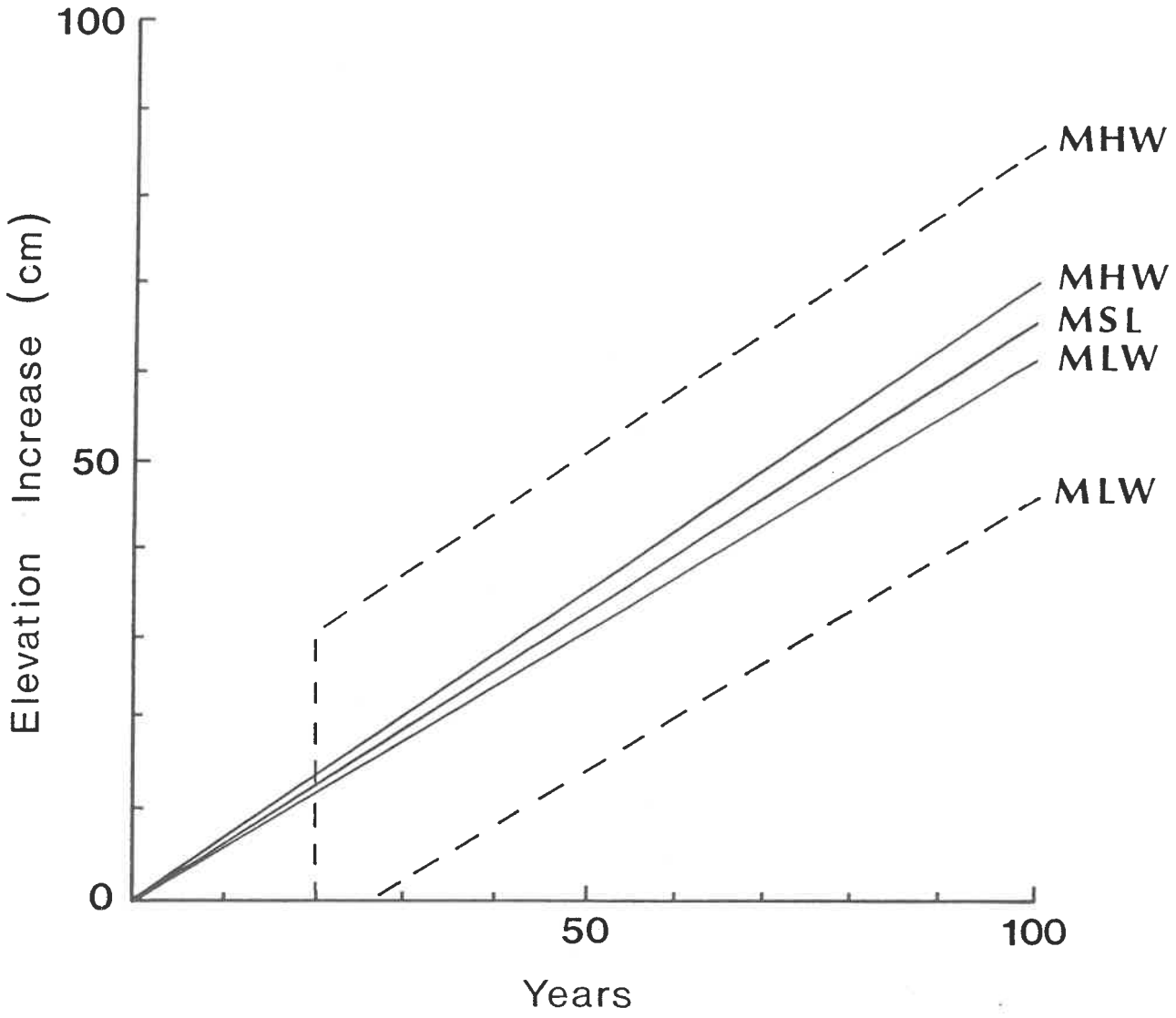

Fig. IV-2. Summary of predicted changes in tidal range and mean sea level, assuming a sea level rise of 50 cm century^{-1} due to the greenhouse effect.
———— no tidal power development
– – – – – – with construction of Cobequid Bay barrage (B9) at year 20. [Effect of a Cumberland Basin barrage (A8) would be much smaller.]
MHW, mean high water; MSL, mean sea level; MLW, mean low water.

transition zones between mixed and stratified areas where vertical mixing supplies abundant nutrients but stratification is sufficient to keep phytoplankton up in the euphotic zone(6). Garrett et al.(7) demonstrated, using Greenberg's(8) tidal model, that these well-mixed frontal areas are formed primarily by tidal mixing. Their analysis, however, failed to pick up the frontal region along the Maine coast identified by satellite imagery which is probably wind-driven(30). All observations indicate that these fronts are fairly consistent in location from year to year.

The only place where the direct relationship between mixing and phytoplankton abundance seems to break down is within the Bay of Fundy. Although mixing increases up the axis of the Bay(7) phytoplankton biomass, as measured by chlorophyll, declines(14) due to increasing turbidity which limits light penetration.

Estimates of annual phytoplankton production are summarized in Table IV-1. The most productive region is obviously Georges Bank which ranks as one of the most productive fishing banks in the world. On average, values for the Gulf of Maine are about half those for Georges Bank and about two thirds of its production occurs in the frontal regions which only occupy 30% of the area(30). Production drops sharply up the Bay of Fundy due primarily to light limitation(21). Not surprisingly, the general pattern of phytoplankton production about the Gulf of Maine and Bay of Fundy matches fish catch very closely(12).

Macroalgae

Macroalgae are especially abundant along the Maine coast and the outer Bay of Fundy where much of the intertidal zone is rocky and the tidal range relatively large. They are less abundant along upper Fundy and the southern Gulf of Maine where sediments dominate the intertidal zone. The fucoids Fucus and Ascophyllum are the major species. Annual primary production is on the order of 750 g C $m^{-2}y^{-1}$ along the central Maine coast(28) and 845 g C $m^{-2}y^{-1}$ in the lower Bay of Fundy(21). Waves and ice export much of the production into coastal water.

Saltmarsh

Saltmarshes commonly occur around the Gulf of Maine and Bay of Fundy in low energy sedimentary environments. Fundy saltmarshes have developed upon thick deposits of marine silt in the upper estuaries such as Shepody Bay, Cumberland Basin and Minas Basin. Massachusetts saltmarshes in contrast are built upon marine peat and usually develop behind protective barrier beaches or at the mouths of rivers(4). A variety of mechanisms appears responsible for the formation of Maine saltmarshes (George Jacobson, personal communication). Fundy saltmarshes are particularly extensive because of the large tidal range and abundant supplies of marine sediment. It is estimated that

Table IV-1. ESTIMATES OF PHYTOPLANKTON PRIMARY PRODUCTION IN THE GULF OF MAINE AND BAY OF FUNDY

Region	Annual Primary Production g C $m^{-2}y^{-1}$	Reference
Gulf of Maine	150-200	Mills 1980 (17)
	180	Sheldon *et al.* 1977 (24)
	415	O'Reilly *et al.* 1981 (19)
Georges Bank	450	Mills 1980 (17)
	665	O'Reilly *et al.* 1981(19)
	400-500	Cohen *et al.* 1981 (5)
SW Nova Scotia	102-128	Mills 1980 (17)
Bay of Fundy		Prouse *et al.* 1984 (21)
Outer Bay	133	
Inner Bay	27	
Upper estuaries	15	

before European colonization, Fundy saltmarshes covered about 360 km^2 but since then most of the high marsh area has been diked for agricultural development. The present saltmarsh area in the Bay of Fundy is about 65 km^2(21). Almquist et al.(1) report that saltmarshes cover approximately 20% of Maine's 5970 km coastline. Jacobson et al.(13) calculate a total saltmarsh area for Maine of 78 km^2, most of which occurs south of Penobscot Bay. They estimate the total marsh area of the entire Gulf of Maine to be twice this.

Saltmarsh ecology studies have focused on the two ends of the Gulf of Maine/Bay of Fundy system, namely Barnstable Harbor on the biceps of Cape Cod(22) and the upper reaches of the Bay of Fundy(9,18,25). Few published studies have been conducted in between, namely Thomas(27) in the Quoddy region and Linthurst and Reimold(16) at Bar Harbor.

Saltmarsh annual net aerial primary production in upper Fundy averages about 215 g C $m^{-2}y^{-1}$(21). This value is very low for North American saltmarshes and production should generally increase toward the southern part of the Gulf of Maine with decreasing latitude(29). Linthurst and Reimold(16) reported that the annual production of Spartina alterniflora at Bar Harbor averaged about 730 g C $m^{-2}y^{-1}$ (assuming a carbon content of 43% dry weight). Jacobson et al.(13) estimated that the net annual primary productivity of saltmarshes along the Gulf is on the order of 10^{11}g y^{-1}. Most of the Fundy low marsh production is exported into coastal water because of the high tidal energy(9). Below ground production is poorly understood. While probably substantial, most of it appears to be utilized in situ.

Sediment Microalgae

Microalgae (primarily diatoms) are ubiquitous in intertidal sediments surrounding the Gulf of Maine and Bay of Fundy. Concentrations tend to be inversely related to sediment grain size and generally greatest on low energy mudflats.

The only detailed studies of sediment microalgal production in the region are those of Hargrave et al.(11) at two sites in upper Fundy. On the basis of these data and sediment chlorophyll concentrations, Prouse et al.(21) estimated that the annual primary production ranged from 9 to 38 g C $m^{-2}y^{-1}$ in different intertidal regions around the Bay of Fundy. Comparable figures are not available for the Gulf of Maine coast but probably fall in the same range.

Total Production

Total annual primary production estimates were prepared for the Bay of Fundy by Prouse et al.(21) and are summarized in Table IV-2. Phytoplankton production dominates the lower part of the Bay while saltmarsh and sediment microalgae dominate the upper

Table IV-2. Primary production estimates for the Bay of Fundy from Prouse et al. (1984) See Fig. 1 for location of regions. Cobequid Bay is the head of Minas Basin east of Economy Point. The Southern Bight is the southern part of the Minas Basin. A line between Digby and Saint John separates the Inner and Outer Bay.

Tonnes C y^{-1} x 10^3

Region	Phytoplankton	Macroalgae	Saltmarsh	Sediment Microalgae	Total	Average (g C $m^{-2}y^{-1}$)
Cumberland Basin	1.2	-	1.6	2.4	5.2	44
Shepody Bay	1.7	-	0.8	2.8	5.3	34
Chignecto Bay	4.2	-	0.2	0.2	4.6	16
Cobequid Bay	3.6	-	0.3	2.4	6.3	21
Minas Basin	10.3	-	0.2	0.8	11.3	17
Southern Bight	2.4	-	2.3	4.1	8.8	41
Inner Bay	125.7	13.5	0.4	0.4	140.0	30
Outer Bay	927.4	13.5	0.4	0.4	942.1	135
	1076.9	27.0	6.2	13.5	1123.6	
	(95.8%)	(2.4%)	(0.6%)	(1.2%)		

estuaries. Macroalgae only make a measurable contribution in the lower Bay. Average total production is greatest at the mouth of the Bay (135 g C $m^{-2}y^{-1}$) and decreases almost an order of magnitude to very low levels in Minas Basin and Chignecto Bay (16-17 g C $m^{-2}y^{-1}$) where waters are very turbid and intertidal areas are relatively small. It increases slightly in the upper estuaries (21-44 g C $m^{-2}y^{-1}$) due to the contribution of saltmarshes and sediment microalgae. Chemosynthetic production is not included in these figures.

Similar total annual primary production estimates have not been prepared for the Gulf of Maine. However, for the purpose of discussion, some very crude estimates are presented in Table IV-3. The total area of the Gulf of Maine is taken to be 1.40×10^5 km^2 of which 1% is coastal(30). The intertidal area was estimated using a coastline length of 8000 km and an average width of 50 m for a total area of 400 km^2. The marsh area is estimated to be 156 km^2(13). The balance is assumed to be half rock and half sediment. Average production rates are based upon data summarized above unless noted otherwise.

As expected, primary production in the Gulf of Maine is overwhelmingly dominated by phytoplankton. Even in the coastal region, phytoplankton appears to be responsible for about two thirds of the production, in sharp contrast to upper Fundy. The macroalgae also appear to be much more important in the coastal region of the Gulf of Maine compared to Fundy. On the other hand, the relative contributions of saltmarsh and sediment microalgae seem much less. The average values for total primary production are much higher in the Gulf of Maine (200-300 g C m^{-2} y^{-1}) than they are anywhere in the Bay of Fundy (16-135 g C m^{-2} y^{-1}).

In summary, all evidence suggests that the Gulf of Maine is more productive than the Bay of Fundy. Both regions are dominated by phytoplankton production. The major limiting factor in the Bay of Fundy is undoubtedly light availability because of the excessive water column turbidity. Large tidal range and abundant intertidal sediment increase the relative importance of production by saltmarshes and sediment microalgae in the upper Bay of Fundy. Clear water and prevalence of rocky coastline favour the dominance of phytoplankton and macroalgae production in the coastal zone of the Gulf of Maine, especially along the Maine coast.

LIKELY IMPACTS OF CHANGING WATER LEVELS

Considerable attention has been given to understanding the environmental impacts of changing water levels that would result from tidal power development in the upper reaches of the Bay of Fundy. Canadian scientists have focused their interests up to the present on the headpond region behind a barrage where water level changes will be most dramatic. Predicted impacts are

Table IV-3. PRELIMINARY PRIMARY PRODUCTION ESTIMATES FOR THE GULF OF MAINE BASED UPON INCOMPLETE DATA

Region	Source	Area(km^2)	Production g C m^{-2} y^{-1}	Production tonnes C y^{-1} x 10^3
Open Gulf	Phytoplankton	138600	200	27,720,000
Coastal	Phytoplankton	1400	250	350 (64%)
	Macroalgae	122	750	92 (17%)
	Saltmarsh	156	641*	100 (18%)
	Sediment microalgae	122	20	2 (1%)
	Coastal total	1800		544
	Coastal average		302	

*Calculated from area and total annual production data of Jacobson et al. (1985).

reviewed in Gordon and Dadswell(10). Much less is known about the impacts seaward of the barrage. Larsen and Topinka(15) have conducted a preliminary evaluation of impacts along the Maine coast. Campbell(2) and Campbell and Wroblewski(3) have more recently conducted detailed studies in the Gulf of Maine.

The impacts of natural changes in water levels, as well as those expected to result from the 'greenhouse effect,' have received little if any attention to date. They will be very similar to the impacts expected from tidal power development since increasing tidal range is involved(23) (Fig. IV-2). Increasing mean sea level will shift the entire intertidal zone upward in elevation and exacerbate flooding problems above present mean high water.

Possible impacts on the four primary producers in the Gulf of Maine and the lower Bay of Fundy are suggested below.

Phytoplankton

Increased tidal range will increase tidal currents as more water moves into and out of the Gulf of Maine and Bay of Fundy on each tide. Garrett et al.(7) have demonstrated that tidal power development would have very little effect on the area of well-mixed frontal regions except for a possible increase between Nantucket Shoals and Georges Bank. Smaller scale changes along the coast of Maine have not been evaluated. Such an increase should promote phytoplankton production since fronts are more productive than stratified regions. On the other hand, increased vertical mixing in existing fronts might decrease production as phytoplankton spend less time in the euphotic zone. It is therefore possible that some regions could experience an increase in phytoplankton production while others experience a decrease. Any significant net effect would be expected to have an important impact on the Gulf of Maine and Bay of Fundy since phytoplankton contribute most of the primary production.

Campbell and Wroblewski(3) have examined the possible effects of tidal power development on Gulf of Maine potential fish production using an ecosystem model. They predict that a 5 to 10% increase in tidal amplitude will increase fish production along the western Maine coast by 7-12% through enhanced vertical mixing and increased phytoplankton production. Fish production along the eastern Maine coast and in offshore waters is predicted to remain at present levels.

Campbell (2, and this volume Ch. VI) has advanced the hypothesis that the Gulf of Maine is a macroestuary. He formulated an energy circuit model based on the premise that the productivity is controlled by import-export exchanges. The model suggests that increased exhange will stimulate production.

Macroalgae

Increased tidal range should increase the area of intertidal habitat available for macroalgae. Assuming that increased tidal currents do not have a negative effect, it seems reasonable that the production of macroalgae will increase because of enhanced nutrient supply.

Saltmarsh

Saltmarshes respond in several ways to increasing sea level(20). Increased tidal range should increase the production of existing saltmarshes(26). It should also increase the export of production to coastal waters. Increasing the elevation of mean high water will give saltmarshes the opportunity to expand in a landward direction. In regions where sediment supply is sufficient, upward marsh growth should keep up to sea level rise. Where not, high marsh should slowly convert to more productive low marsh. At the present level of understanding, the likely impacts on saltmarsh production seem mostly positive. Both Fundy(9) and Maine marshes (Peter Larsen, personal communication) are currently subjected to erosion which should increase with rising sea level.

Sediment Microalgae

Increased tidal range should increase the area of intertidal sediment flats which, other factors being equal, should increase the production of sediment microalgae. Increased tidal currents on the other hand may lead to coarser sediments which would reduce production. The effect of any net impact should be very small since sediment microalgae seem to contribute such a small amount of the total primary production in the Gulf of Maine coastal zone (Table IV-3).

SUMMARY

Present understanding is insufficient to make exact predictions of the effects of increasing tidal range and mean sea level on primary production in the Gulf of Maine and Bay of Fundy. However, in general terms, the net impact of the various gains and losses averaged over the entire region will probably be small and difficult to detect above natural variation. Localized impacts will probably be visible at a number of coastal locations. The most critical impact will be that on the phytoplankton which overwhelmingly dominate the primary production.

More precise predictions in the Gulf of Maine require the following information, listed in order of priority:

1. Phytoplankton
   - More detailed mapping of the distribution of phytoplankton biomass, production and interannual variability, especially in the coastal zone.
   - Improved understanding of the relationships between phytoplankton production and water column mixing/stratification processes.

2. Macroalgae
   - Detailed mapping of rocky intertidal habitat.
   - More biomass and productivity measurements at selected sites.
   - Improved understanding of the importance of tidal currents on production.

3. Saltmarshes
   - Detailed mapping of saltmarsh area, elevation and vegetation.
   - More productivity/export measurements at selected sites.
   - Improved understanding of the ecological importance of exported production.

4. Sediment microalgae
   - Detailed mapping of sediment intertidal habitat and microalgal biomass.
   - Productivity measurements at selected sites.
   - Improved understanding of the effects of increasing tidal currents on intertidal sediment grain size and microalgal biomass.

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V. A BRIEF REVIEW OF BENTHIC COMMUNITIES OF THE GULF OF MAINE AND BAY OF FUNDY WITH REFERENCE TO TIME AND TIDES[1]

Peter F. Larsen

INTRODUCTION

The Gulf of Maine-Bay of Fundy system is a semi-enclosed, macrotidal sea, strongly influenced by a continental climate. Its complex topography and hydrography, in combination with a recent and rapid geological evolution, have created a highly productive, ecologically unique, system. Over the last few thousand years major changes have occurred in both sea level and tidal range. These physical alterations have had, and continue to have, a great influence in shaping the biological character of the Gulf of Maine system. Presently it would seem that both sea level and tidal range in the Gulf of Maine-Bay of Fundy system may be further altered by man's activities. This will undoubtedly produce responses in the biological system.

The purpose of this paper is to initiate a discussion of how the impending modifications of basic physical forcing functions might influence the benthic macroinvertebrate communities in the Gulf of Maine-Bay of Fundy system. I begin with a brief overview of the benthic communities of the region with emphasis on several unique features that may be related to past and present hydrographic conditions. Next, I discuss the distribution of sand beach communities in terms of tidal mixing patterns. This is followed by some archaeological evidence supporting the contention that previous sea level changes have resulted in the appearance and disappearance of benthic faunas. Finally, I speculate on what sort of biotic changes might be expected from predicted changes in sea level and tidal range. I wish to emphasize the preliminary nature of this paper. I have made no effort to be comprehensive but hope some points are made convincingly enough to stimulate further thought and discussion.

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BENTHIC COMMUNITIES

Although the Gulf of Maine-Bay of Fundy system is assigned to the boreal Acadian biogeographic province, subregions of this area range from warm-water pockets characterized by species of Virginian affinities to tidally well mixed expanses dominated by subarctic fauna(3). The resulting diverse fauna which is readily available intertidally, has made the Gulf of Maine, especially its physiographically complex Quoddy region, a mecca for naturalists and taxonomists. Indeed, during the nineteenth and early twentieth centuries, much of the fauna of the northwest Atlantic was described from this area. In spite of the voluminous systematic and taxonomic literature from the Gulf of Maine region, quantitative descriptions of the region's macrobenthic communities are not very complete. The situation in the Bay of Fundy area has recently been reviewed(21,22,23) so I will limit my remarks to the Gulf of Maine proper, with emphasis on the coastal zone of the northern Gulf.

Subtidal Benthic Communities

Quantitative descriptions of offshore benthic communities in the Gulf of Maine are especially scarce. I am aware of only one published account which is that of Rowe *et al.*(17), which described the fauna of Wilkinson and Murray Basins. A large amount of information compiled by the National Marine Fisheries Service is being summarized by Theroux and Wigley, but this material is not generally available. In addition, researchers at both the University of Maine and the Bigelow Laboratory have recently undertaken several cruises in the Gulf of Maine which may result in community descriptions in the near future. These efforts indicate that the offshore regions of the Gulf are characterized by low benthic densities.

The communities of hard substrata, both offshore and in the coastal region, are being examined by investigators at the University of Maine, the University of New Hampshire and Northeastern University.

Only four quantitative studies of coastal soft-bottom communities in the northern Gulf of Maine have been published and each of these is extremely limited in its geographic extent. Hanks(6) described the communities in two coves in the lower Sheepscot Estuary. The same stations were occupied 18 years later by Larsen(7) who documented dramatic changes in density, dominance and species composition. Bilyard(2) catalogued the invertebrate fauna associated with the scaphopod *Dentalium stimpsoni* just offshore of Boothbay Harbor and Shorey(20) studied the community inhabiting sawdust bearing sediments in the upper Penobscot River estuary.

In the last decade, larger scale benthic surveys of Penobscot Bay, Casco Bay, Massachusetts Bay and the Sheepscot

River Estuary have been undertaken. Much of the data is only available in report form(9,13,15). Comparisons of these results with those of similar studies in other temperate and boreal regions indicates that Gulf of Maine subtidal macrobenthic communities rank relatively high in terms of both density and species richness. For example, mean density in Casco Bay, Penobscot Bay and the Sheepscot Estuary ranged from 3,475 to 8,743 individuals m^{-2} with an overall mean of 5,715 m^{-2}. By comparison, five other studies using the same methodology exhibited a density range of 722-4,198 m^{-2} with a mean of 2,255 m^{-2}. The same northern Gulf of Maine embayments harbored 231-470 species each for a mean of 362 species per site. Six other sites worldwide manifested between 33 and 298 species for a mean of 255.

Intertidal Benthic Communities

Intertidal communities have received more investigation than subtidal communities. This is especially true of the rocky shore intertidal which has received considerable attention from the faculty and students of the University of Maine as well as from individuals from throughout the United States. Several publications are available describing different aspects of the ecology of rocky shores.

The communities of sandy shores in southern Maine and New Hampshire have been extensively studied by Croker and his students from the University of New Hampshire. The more northern sand beaches and other sedimentary intertidal habitats have been sampled by Larsen and his colleagues. These data are available in publications or report form(8,11,12,14) and one data set will be discussed briefly below.

Some Unique Features

There are several unique features of the benthic fauna of the Gulf of Maine that need to be emphasized. The first is the vast species richness. About 1500 species of benthic invertebrates have been identified from the Quoddy region and 1400 species are included in a draft checklist of the benthic invertebrates of the Maine coast(4). This is about twice the number of species found in checklists from other areas of the east coast. The northern Gulf of Maine is arguably the most diverse region in eastern North America north of the tropics(24).

In eastern Maine many species can be found intertidally that are confined to the subtidal in other regions. Some notable examples from Cobscook Bay include brachiopods, priapulids and five species of *Astarte*. Based on the intertidal surveys and literature used in compiling the checklist mentioned above, Larsen and Doggett (unpublished) were able to produce a list of 99 species which were found intertidally only in eastern Maine.

In the Quoddy region several species exhibit the phenomenon of giantism. In Cobscook Bay it is not unusual to find periwinkles, starfish and sea urchins that are two or three times their normal size.

We believe all of these phenomena can be related to the oceanographic conditions and, in particular, to tidal mixing. Tidal mixing dampens the seasonal fluctuation of temperature allowing the survival of both cold- and heat-sensitive species. The cool summer water temperatures produce an abundance of fog which protects intertidal species from desiccation. Eastport, Maine is foggy on 40% of the days in July. We speculate that giantism is related to tidal mixing either through lengthening of the feeding season (i.e., by accelerating growth) or by delaying sexual maturity as a function of reduced summer temperatures and thereby allowing for longer somatic growth.

COMMUNITY COMPOSITION AND OCEANIC FRONTS

Water column stability plays a role in structuring benthic communities as is evidenced in the distribution of sand beach fauna in the northern Gulf of Maine(8). Cluster analysis of the data from eight beaches formed three geographically distinct groups that could not be explained by difference in wave exposure or sediment type. Physical oceanographic data suggested that temperature might be the operative ecological mechanism. Examination of thermal satellite images showed the existence of seasonally persistent thermal features which correspond very well with the distribution of the objectively and independently defined faunal assemblages. These thermal features are the Fundy and Jeffreys Bank frontal areas, in eastern and central Maine respectively, and the highly stratified area in the western Gulf of Maine. The supposition is that the existence and intensity of vertical mixing determines the surface water temperature which, in turn, is a factor which can influence the distribution of littoral fauna.

ARCHAEOLOGICAL EVIDENCE

Archaeological evidence that sea level rise can have a profound effect on the development of benthic communities comes from the Damariscotta River estuary, Maine(10). In the upper Damariscotta River are located Indian shell middens that are remarkable not only for their size (up to nine meters thick) but because they are principally composed of American oyster shells, a species which no longer reproduces in the River. Evidence indicates that these middens began to accumulate about 2500 years BP and continued until about 500 years BP. Since shellfish utilization occurred in the region from at least 5200 BP, it is assumed that oyster utilization was a simple function of their availability, i.e., the species appeared and flourished in the

upper Damariscotta for about 2,000 years and then died out. Early researchers of these middens were quick to invoke sea level rise as the causal environmental factor in the appearance and subsequent disappearance of the oyster. Presently, only two natural populations of oysters survive along the northern New England coast.

It is believed that about 2500 years BP sea level rose high enough for saline water to pass over a sill in the upper Damariscotta River. This produced a warm, shallow area with sufficient salinity for the oyster to flourish. For the next 2000 years it is believed that sea level rose very slowly, maintaining this superior oyster habitat. This is consistent with the views of Scott and Greenberg(19) on rates of sea level rise.

Three theories exist for the subsequent disappearance of the oysters:

1) Pollution from lumbering or agricultural activities of the early colonists;

2) A decrease in water temperature caused by the ever deepening sea, i.e., as more sea water poured over the sill temperatures fell below the breeding threshold of the oysters; and

3) The rising sea level increased the salinity to the point where predators and competitors were able to invade.

We probably will never know which of these factors, singly or in combination, was responsible for the demise of the Damariscotta oyster beds and the associated fauna, but the third is perhaps the most plausible. Early colonial lumbering and farming also occurred on the adjacent Sheepscot estuary and oysters still survive there today. The present day water temperatures in the upper Damariscotta estuary seem sufficient for oyster reproduction. These facts reduce our confidence in the first two theories. Supporting the third theory is evidence that oysters low in the middens show fewer signs of associated boring species than those high in the middens(16). This suggests that as salinity rose with the sea level, the community became more complex and biologically stressful until the oyster itself was eliminated. An increase in the tidal range could be expected to produce the same results.

TOWARDS THE FUTURE

In the above we have seen that the Gulf of Maine contains a very rich macrobenthic fauna. This fauna also exhibits certain unusual features, such as intertidal occurrences of normally subtidal species, and giantism, which are probably related to tidal mixing. In addition, there is strong evidence that

patterns of water column structure, often a function of tidal mixing, are factors influencing the distribution of certain benthic communities. Finally, archaeological evidence demonstrates that sea level rise can account for the appearance and disappearance of individual species and entire estuarine communities. With this background it is possible to engage in some very preliminary speculation on how the benthic fauna of the Gulf of Maine-Bay of Fundy system might respond to further rises in sea level and an increase in tidal range.

A larger tidal range will produce stronger tidal currents which could influence benthic species and community development through changes in temporal and seasonal patterns of primary productivity, rate of supply of food to suspension feeders, modification of sedimentary environments, etc. Although these effects may be important, and deserve thorough consideration, they are indirect consequences which are best considered in a more general context. This discussion will be limited to the direct influence of the modified physical regime on benthic organisms.

Stronger tidal currents will enhance tidal mixing in many areas. Although Garrett et al.(5) conclude that the Great South Channel will be the only area to be significantly affected by increased mixing, the scale of their model is too large to detect the many localized areas where increased mixing could be biologically important. An example would be island mixing zones such as that around Monhegan Island. These areas, which undergo biological changes over spring-neap tidal cycles(1) will be shifted towards their spring tide configuration. The result vis a vis the benthos will be reduced temperature variation and, hence, reduced stress. We can expect that species rich areas that are presently maintained by tidal mixing will be enhanced and expanded.

Some of the most dramatic effects of sea level rise and tidal range alteration will be manifested in estuaries. A larger tidal excursion will enhance the dispersion of larvae. This may lead to greater gene flow between mesohaline and oligohaline populations in neighboring estuaries, but it also might lead to the export of enough larvae from a particular estuary to reduce the reproductive success of isolated parent populations. The rate at which certain groups, such as the peracarid crustaceans, are expanding their ranges could be expected to accelerate.

Higher tides and elevated sea level will increase ocean water penetration into estuaries and result in modifications such as occurred prehistorically in the Damariscotta Estuary. The reduced temperatures associated with the landward penetration of cool sea water will erode the pockets of Virginian fauna for which some Gulf of Maine estuaries, such as the Sheepscot, are noted. In particular, we may expect the American oyster, the quahog, xanthid crabs, and other species requiring warm water for reproduction, to disappear from the northern Gulf of Maine. The concommittant increase in salinity will allow the

introduction of predators, competitors and even diseases, which were previously excluded by their limited tolerance to reduced salinities, further hastening the demise of existing estuarine communities.

The unusual geomorphology of some of our estuaries makes them particularly susceptible to rapid faunistic changes due to salinity intrusion. The upper Sheepscot estuary is protected by a sill which prevents the salinity from rising above $20^{o}/_{oo}$. At the head of the Kennebec estuary lies Merrymeeting Bay, one of the largest tidal freshwater habitats in North America. It is also protected from significant intrusions of salt water by a sill. Higher ocean levels will cause an increased flow of salt water over these sills resulting in salinity stresses which will dramatically modify the biota. This is especially true in Merrymeeting Bay which could change from a freshwater to a brackish water habitat.

Many rivers in the northern Gulf of Maine have a steep slope extending all the way to the coastal zone. The result is that the tidal portion of their estuaries reaches to the fall line. Some estuarine faunal zones are not fully developed because salt water extends to the fall line(10). In many of these estuaries a significant rise in sea level could result in the compaction, or even truncation, of estuarine faunal zones. In other words, a rise in sea level will not result in a landward migration of estuarine zones as might be the case in coastal plain estuaries, but will result in the diminution, or even loss, of the tidal freshwater, oligohaline and even mesohaline zones. Such changes are highly predictable.

The degree of physiological stress an estuarine organism experiences is a function of the rate of change of salinity and this is a dominant factor in the structuring of estuarine communities. The rate of salinity change over a tidal cycle in an estuary is related to the tidal prism, the freshwater flow and the volume of the estuary. Both sea level rise and tidal range modification can increase the salinity fluctuation over a tidal cycle by effectively reducing the volume of the estuary and by increasing the tidal prism, respectively. The ecological result is that most estuaries in the northern Gulf of Maine will become more poikilohaline with associated shifts in fauna. Physical changes of this sort can be predicted with methods and data now available. Unfortunately, more needs to be known about the biological components of these estuaries before the ecological consequences can be evaluated.

SUMMARY

The above preliminary consideration of the potential consequences of sea level rise and increased tidal range to the benthic communities of the Gulf of Maine can be summarized by six general points:

1. The Gulf of Maine supports a rich benthic fauna;
2. Many unique faunal features can be related to tidal mixing;
3. Community distribution can be related to tidal mixing;
4. Sea level rise can be shown to influence community development;
5. Some predictions can presently be made on the effects of sea level rise and tidal changes; and
6. The accuracy of the predictions could be increased significantly with further research.

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VI. POSSIBLE EFFECTS OF FUNDY TIDAL POWER DEVELOPMENT ON PELAGIC PRODUCTIVITY OF WELL-MIXED WATERS ON GEORGES BANK AND IN THE GULF OF MAINE

Daniel E. Campbell

INTRODUCTION

The present marine ecosystem of the Gulf of Maine and Bay of Fundy is greatly influenced by tidal energy. Greenberg(16) used a mathematical hydrodynamic model of the Gulf of Maine and the Bay of Fundy to predict that construction of a proposed dam across the Minas Basin in the upper Bay of Fundy would result in an average 10% increase in tidal amplitudes along the U.S. and Canadian coasts. Garrett(12) estimated that this increase would amount to a 5% change in tidal velocities averaged over the entire Gulf of Maine. Since the energy in tidally driven mixing is proportional to the cube of tidal velocity, a 5-10% velocity change results in a 16-33% change in tidal mixing energy. High levels of summertime primary production in the Gulf of Maine have been shown to be largely dependent upon the nutrients supplied by vertical and horizontal mixing processes along tidal mixing fronts(42). For this reason any alteration of the energy available for tidal mixing could have an important effect on marine ecosystem productivity on Georges Bank and in the Gulf of Maine.

Primary production in the well-mixed waters on Georges Bank and in the Gulf of Maine from May to October is largely controlled by the interaction of available solar radiation with nutrients supplied by physical mixing processes(23,42). Garrett et al.(13) demonstrate that frictionally dissipated tidal energy is largely responsible for creating and maintaining these well-mixed areas. In addition, Loder and Greenberg(22) presented evidence that wind is an important factor determining the extent of mixed areas in the Gulf of Maine. Campbell and Wroblewski(4) formulated a simple mathematical model which described the tradeoff between light and nutrient limitation experienced by phytoplankton in waters mixed by a combination of wind and tidal energies. Their model included a simple pelagic food chain which allowed the effect of altered primary production on pelagic fish production to be estimated. This model is used here to evaluate the possible effects of increased mixing on the pelagic fish

production of Georges Bank, the SW Nova Scotian coast, and along the coasts of eastern Maine and New Brunswick.

MODEL DEVELOPMENT

Spatial boundaries for subsystems within the Gulf of Maine which might be affected by increased tidal mixing brought about by construction of a tidal power dam at the B9 site in the upper Bay of Fundy are defined in Fig. VI-1. The total area shallower than 100 m was assumed to be an estimate of the maximum extent of the influence of tidal mixing. This area was then divided according to the distribution of stratified versus vertically mixed areas (cf. 13,42). This division led to the separation of the stratified western and central portions of the Gulf (D & E, Fig. VI-1) from the well-mixed waters of eastern Maine (Fig. VI-1,C) SW Nova Scotia (Fig. VI-1,B) and Georges Bank (Fig. VI-1,A). The stratified areas D and E and the well-mixed area C in Fig. VI-1 have been considered elsewhere(4). Here I evaluate the possible effects of increased tidal mixing on the well-mixed waters of areas A, B. and C in Fig. VI-1 during the half year (0.5 yr) from May to October when primary productivity in the Gulf is largely controlled by the extent of mixing(42).

Iles and Sinclair(17) hypothesized that the stock size and productivity of herring may be dependent on the size and productivity of larval retention areas which are also the spawning areas in well-mixed waters of the Gulf of Maine. They pointed out that herring spawning areas in the Gulf of Maine and on Georges Bank correspond closely with the areas of strong tidal mixing shown by Garrett et al.(13). Graham(14) has demonstrated that estuaries are the areas of overwintering herring larval retention along the Maine coast but the larvae also depend on coastal production for survival(37). Results indicate that most of the herring larvae spawned along the eastern Maine coast are retained by estuaries in area C of Fig. VI-1(15). Therefore, areas A, B, and C in Fig. VI-1 include most of the spawning and larval retention area for herring stocks on Georges Bank, SW Nova Scotia and eastern Maine and New Brunswick, respectively.

For this model the hypothesis of Iles and Sinclair(17) is assumed to be correct. In addition pelagic productivity was considered to be representative of a moderately exploited herring fishery within which the majority (90%) of pelagic production is accounted for by herring(34). Herring production is dependent upon primary production through a simple food chain leading from phytoplankton through zooplankton to fish. Pelagic fish do not use all zooplankton production, and more than half of the zooplankton production remains to support benthic food webs and other pelagic predators.

Primary production is controlled by the interaction of light and nutrients modulated by mixing. Mixing increases the supply of nutrients enhancing primary production, but it also carries

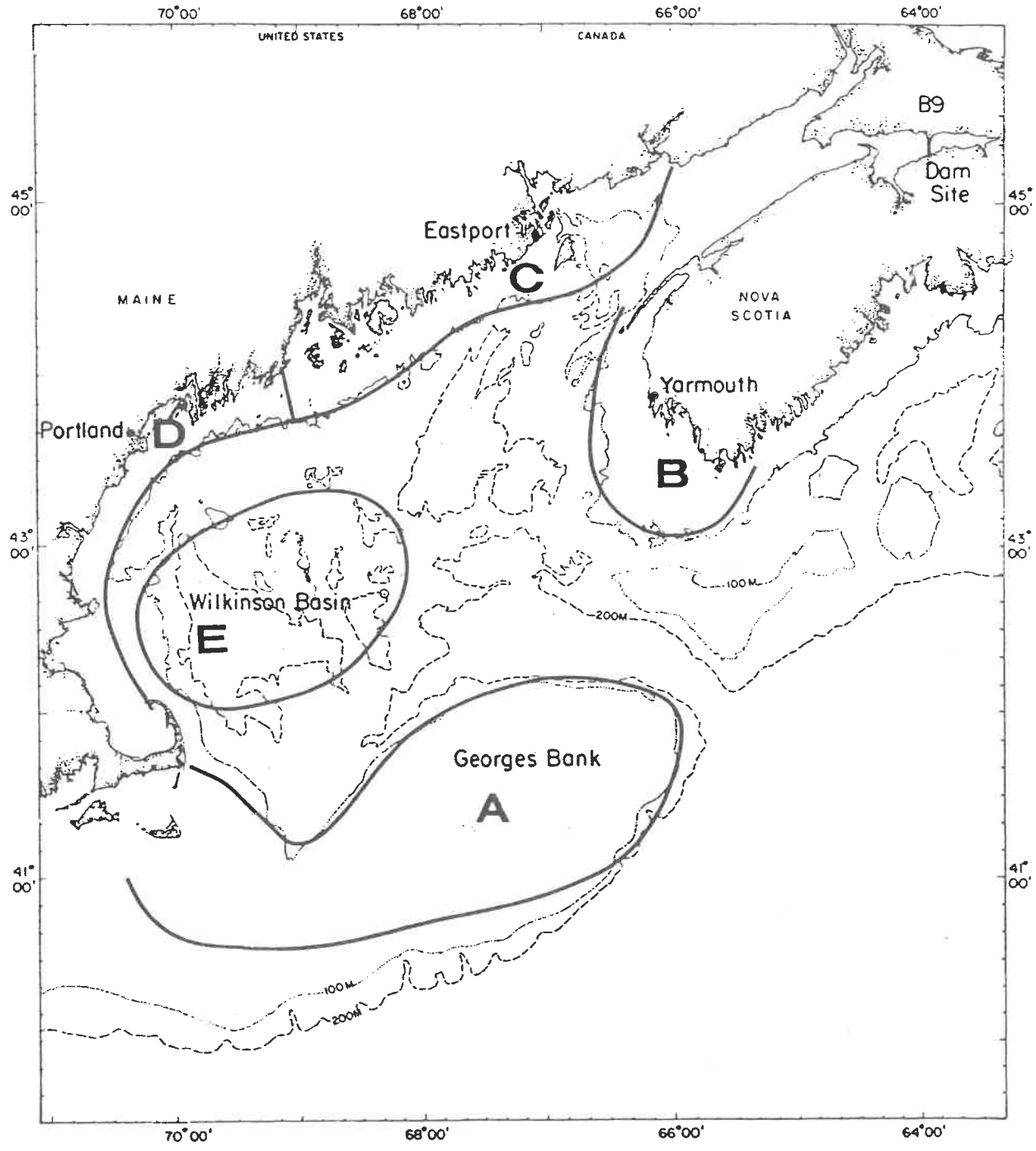

Fig. VI-1. Boundaries of the subsystems within the Gulf of Maine defined on the basis of their vertical mixing characteristics.

phytoplankton cells out of the euphotic zone decreasing primary production. In this analysis the idea of mixing is generalized and therefore both horizontal and vertical mixing processes are included in the analysis. For example, the Georges Bank case uses the deep nitrogen concentration found from 65-120 m surrounding the well-mixed area shallower than 65 m. In this case mixing energies include vertical and horizontal mixing processes and both are assumed to be roughly proportional to the amount of available kinetic energy in the water column.

Figure VI-2a, b, and c shows the evaluated energy circuit models representing the pelagic ecosystems of Georges Bank, the SW Nova Scotian coast, and the eastern Maine and New Brunswick coasts, respectively. The model is discussed in detail elsewhere(4). In the energy circuit language(25,26) each symbol has a precise mathematical definition and the equations for this model are given in Table VI-1. A detailed description of the model and the methods used in its evaluation are presented in Appendix VI-1.

SIMULATION METHODS

The models shown in Fig. VI-2 were simulated and the sensitivity of fish yield, J_{11}, and nitrogen storage, N, to changes in the amount of tidal energy available for mixing were recorded for several values of the tidal energy mixing efficiency. This analysis was performed by first running the evaluated models to obtain steady state values for the storages and flows. In subsequent runs the amount of tidal energy input to the model was changed and the response of the model variables to this change was noted after the new steady state values (those corresponding to the altered input) were obtained. The sensitivity of the model to variations in solar energy input was examined in a similar fashion. All model runs were for a period of two simulated summers and steady state values were recorded at the end of this period. The results of this sensitivity analysis were expressed as plots of dimensionless variables in which the new steady state values (the steady state value after perturbation) was scaled or divided by the original steady state value.

SIMULATION RESULTS

The evaluated models shown in Fig. VI-2 show that wind mixing is most important (relative to tidal mixing) along the eastern Maine and New Brunswick coasts and least important on Georges Bank. The largest fish yield per square meter was found off SW Nova Scotia which was also the area with the most available mixing energy and the largest primary production per square meter. The high productivity values shown for Georges Bank and SW Nova Scotia are heavily dependent upon nitrogen

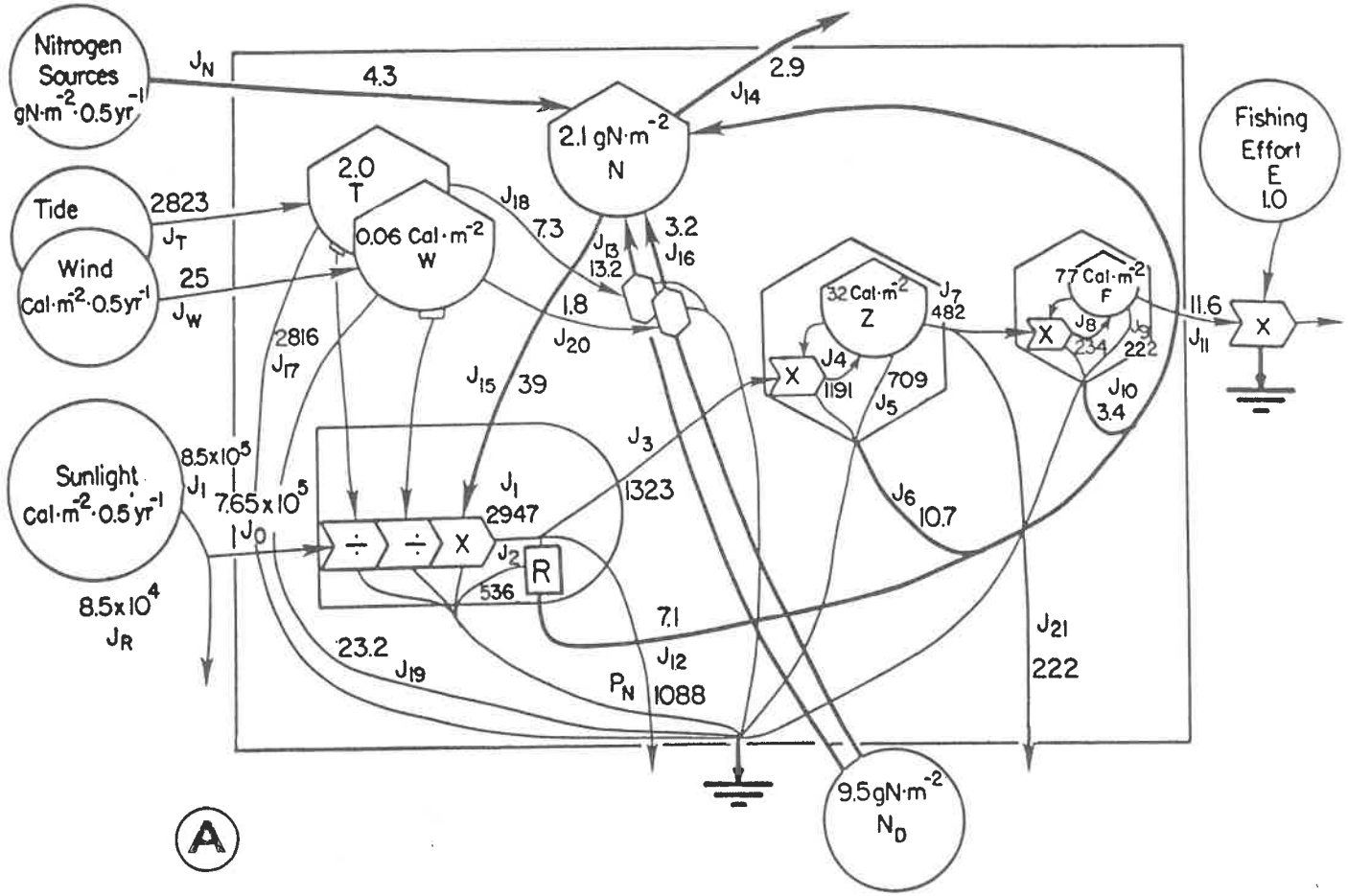

Fig. VI-2A. Energy circuit diagram for Georges Bank. External energy sources and internal pathways are fluxes identified by J_i in the diagrams. Flows of matter are drawn in boldface and have units of g N m^{-2} 0.5 yr^{-1}. Other numbered pathways are flows of energy with units of Cal m^{-2} 0.5 yr^{-1} (see Appendix). [1 kilocalorie (Cal) = 4183 joules.]

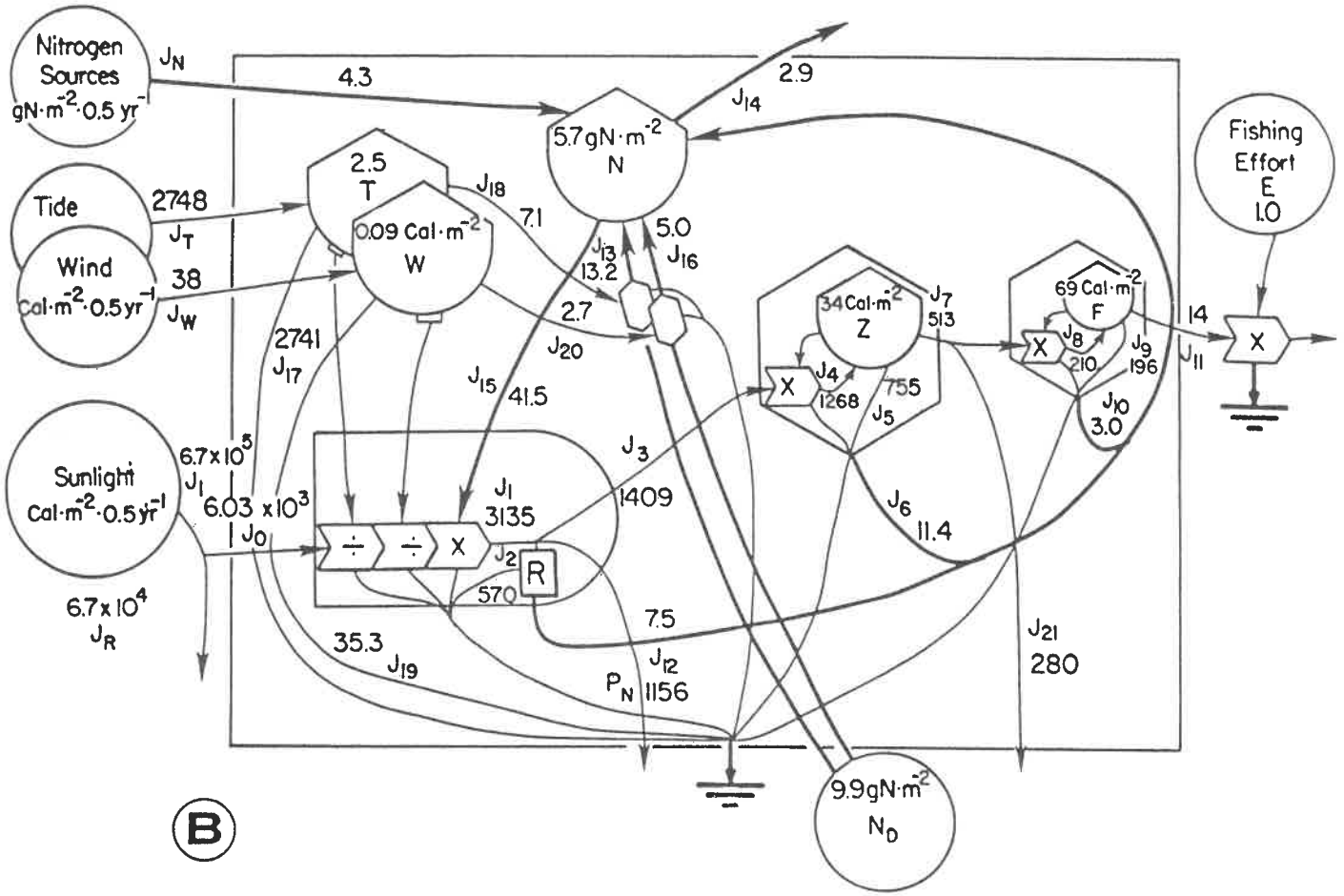

Fig. VI-2B. Energy circuit diagram for SW Nova Scotia. Symbols as Fig. VI-2A.

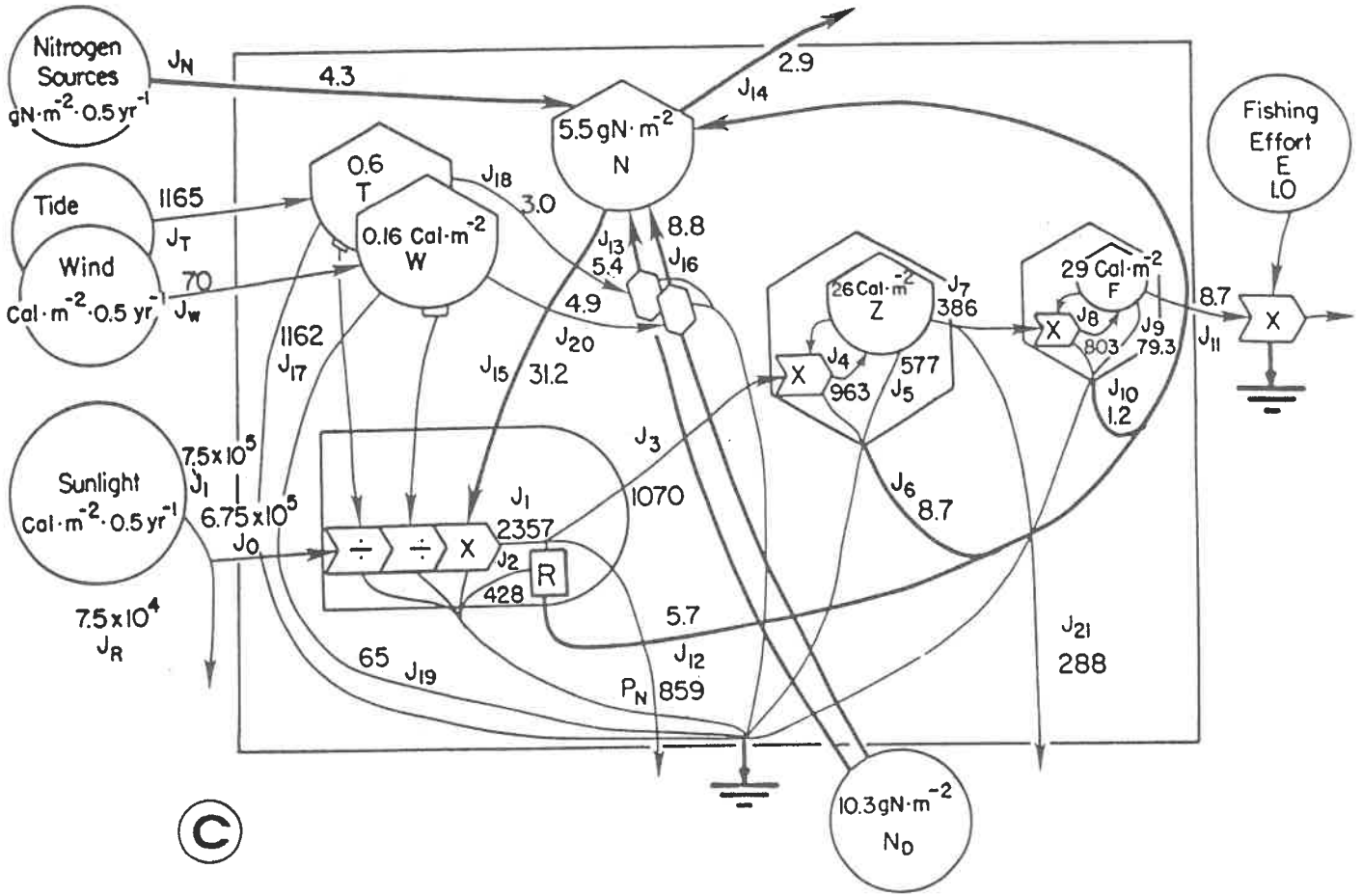

Fig. VI-2C. Energy circuit diagram for eastern Maine and New Brunswick coasts. Symbols as Fig. VI-2A.

Table VI-1. Equations describing the models in Fig. VI-2A-C. See Appendix VI-1 for definitions of component variables, Q, and pathway flows, J, where $J_I = k_I Q$, and k_I is a transfer coefficient.

(1) $$J_R = \frac{J_I}{1 + k_O N/WT}$$

(2) $$P_N = \frac{k_1 N J_R}{WT(1 + k_2 + k_3 Z)}$$

(3) $$dZ/dt = k_4 Z P_N - k_5 Z - k_7 Z F$$

(4) $$dF/dt = k_8 Z F - k_9 F - k_{11} F E$$

(5) $$dN/dt = J_N + k_{16}(N_D - N)W + k_{13}(N_D - N) + k_{12} P_N + k_6 Z + k_{10} F - k_{15} J_R N/WT - k_{14} N$$

(6) $$dT/dt = J_T - k_{17} T - k_{18}(N_D - N)T$$

(7) $$dW/dt = J_W - k_{19} W - k_{20}(N_D - N)W$$

supplied by mixing processes. However, Georges Bank has 26% more solar energy available to support primary production than does SW Nova Scotia. The balance between solar radiation and nitrogen supplied by mixing energy is seen in the sensitivity of pelagic fish yield and nitrogen storage to changes in the amount of available tidal energy (Fig. VI-3 and VI-4, respectively).

Georges Bank

An increase in tidal energy results in an increase in the yield of pelagic fish from Georges Bank (VI-3a). When tidal energy was decreased, pelagic fish yield fell sharply. This pattern was similar for mixing efficiencies of 2.6 and 0.26%, but the higher mixing efficiency was more sensitive to changes in tidal energy input.

Nitrogen in the water column was a monotonically increasing function of tidal energy input. Nitrogen in the water was also most sensitive to changes in tidal energy for the higher mixing efficiency.

Table VI-2 shows the changes in pelagic fish productivity corresponding to the predicted increase in tidal mixing energy as well as the changes caused by similar decreases in tidal mixing. The most probable result for Georges Bank is a 1.5 to 2.3% increase in pelagic fish production corresponding to a 5% increase in tidal velocities and a 16% increase in tidal mixing energy on the bank. Table VI-3 shows that this change is similar to the variation in pelagic fish production caused by changes in solar energy input of 1 to 3%.

SW Nova Scotia

The variation of fish yield with changes in tidal energy exhibits a different pattern in SW Nova Scotian waters (Fig. VI-3b). Here an increase in tidal energy causes a small decrease in pelagic fish yield, whereas 16% and 33% decreases in tidal energy bring about small increases in pelagic fish production. Pelagic fish yield falls off sharply for larger decreases in tidal energy for the higher mixing efficiency, but yield continues to rise for a 50% decrease in tidal energy at the lower mixing efficiency. Unlike Georges Bank pelagic fish yield is most sensitive to increased tidal energy at the lower mixing efficiency of 0.26%.

Figure VI-4b shows the variation of nitrogen in the water column for changes in tidal energy. The variation is similar to that observed for Georges Bank in that nitrogen increases monotonically with tidal energy and the model is most sensitive to the higher mixing efficiency. One difference between the two curves is that the Georges Bank curve has an inflection point at the present value of tidal mixing energy, whereas the slope of

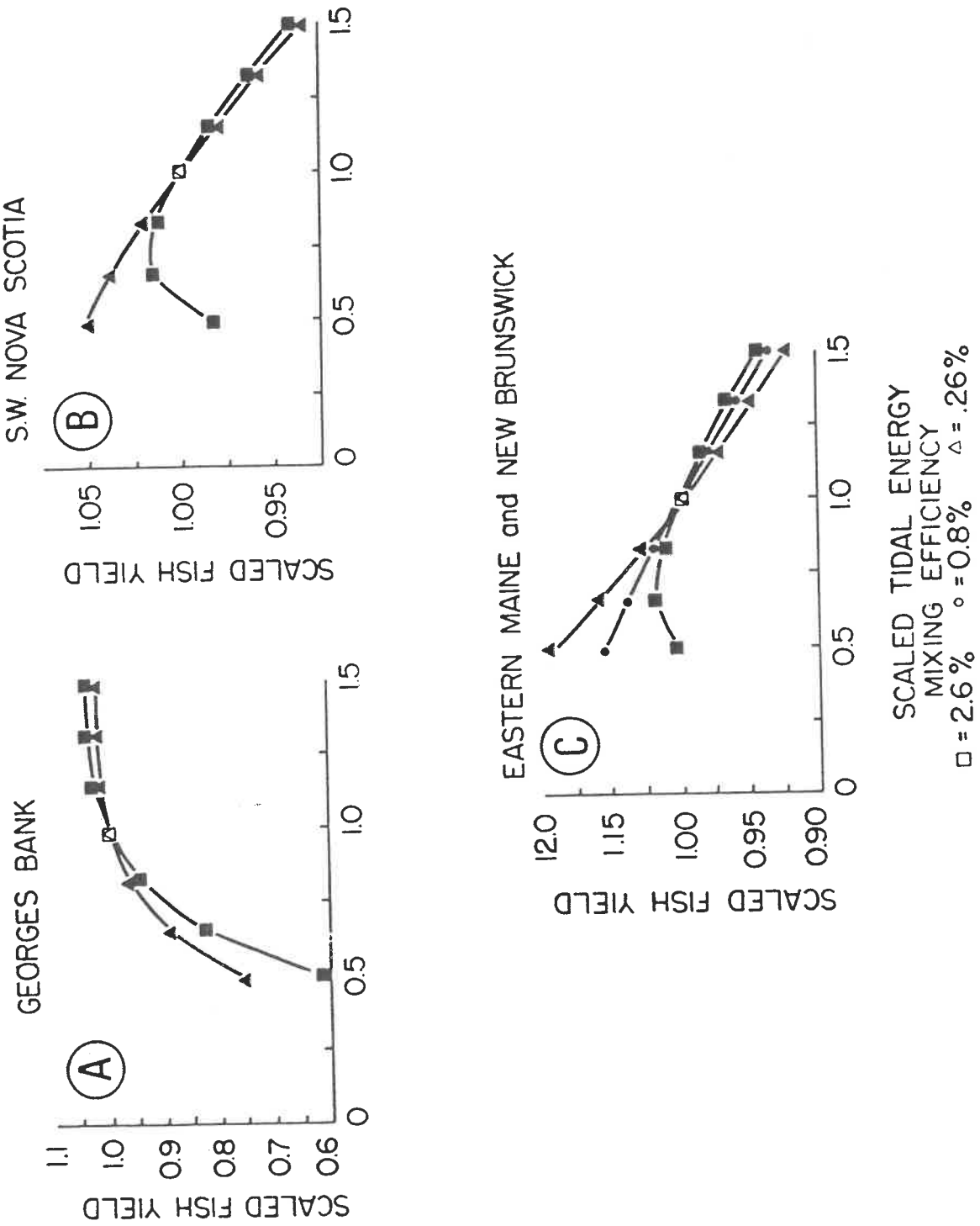

Fig. VI-3. Response of fish yield to changes in the tidal energy on (A) Georges Bank; (B) SW Nova Scotia coast; (C) eastern Maine and New Brunswick coasts for several mixing efficiencies.

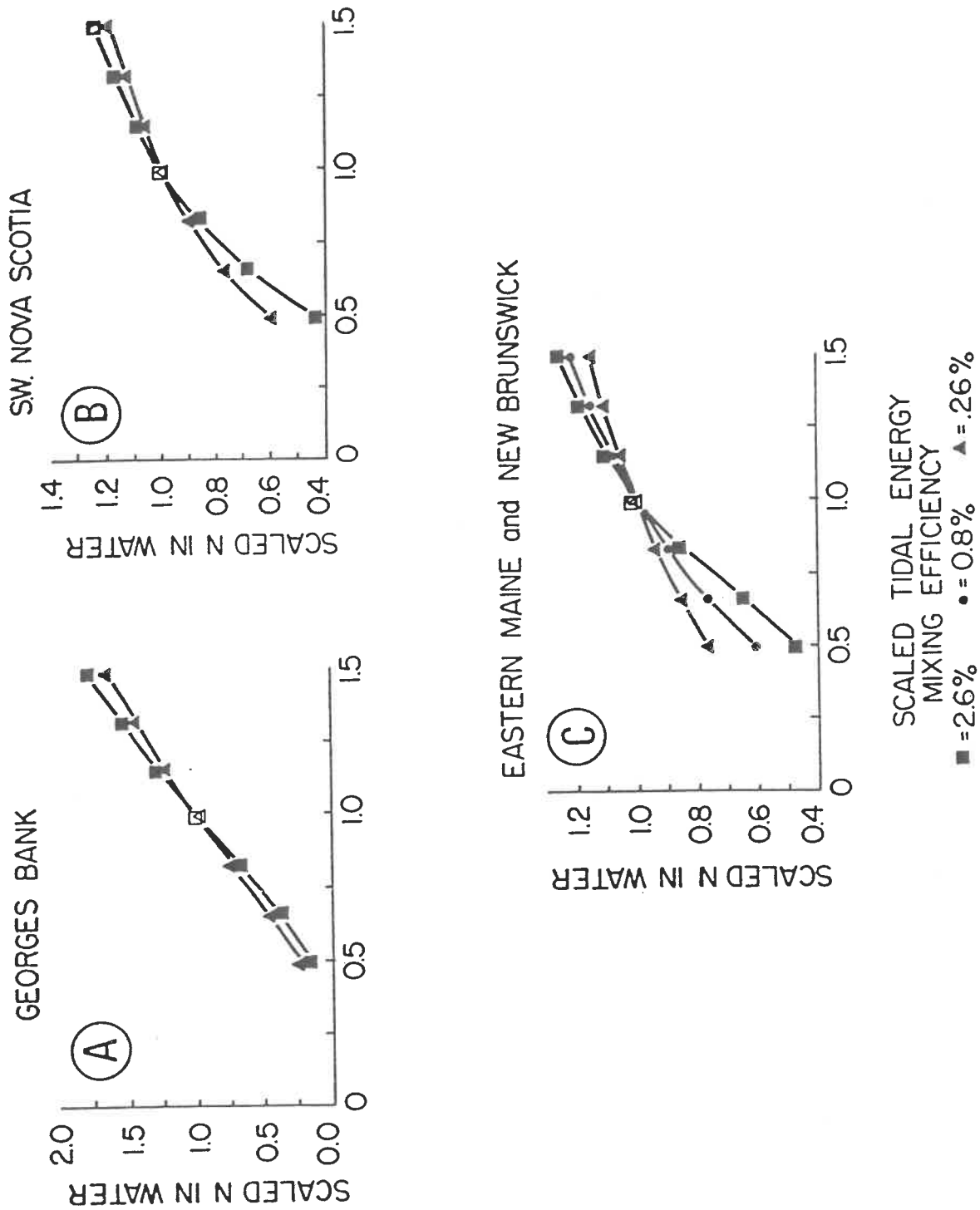

Fig. VI-4. The response of Nitrogen (N) in the water to changes in tidal energy on (A) Georges Bank; (B) SW Nova Scotian coast; (C) eastern Maine and New Brunswick coasts for several mixing efficiencies.

Table VI-2. Percentage changes in pelagic fish yield resulting from tidal mixing energy increases and decreases for Georges Bank (A), SW Nova Scotia (B), and the eastern Maine and New Brunswick ecosystems (C). The predictions are shown for tidal mixing efficiencies of 2.6% and 0.26%.

	Percent Change in Tidal Energy			
Location[1]	33	16	-16	-33
A Georges Bank				
Mixing Eff.=2.6%	3.3	2.3	-5.1	-17
Mixing Eff.=0.26%	2.2	1.5	-3.3	-10.5
B SW Nova Scotia				
Mixing Eff.=2.6%	-3.8	-1.8	1.3	1.7
Mixing Eff.=0.26%	-4.3	-2.1	2.0	3.9
C Eastern Maine and New Brunswick				
Mixing Eff.=2.6%	-3.6	-1.7	1.3	2.0
Mixing Eff.=0.26%	-5.1	-2.6	2.7	5.9

[1]Refer to Fig. VI-1

Table VI-3. Percentage changes in pelagic fish yield resulting from changes in available solar energy for Georges Bank (A), SW Nova Scotia (B), and the eastern Maine and New Brunswick ecosystems (C). The predictions are shown for a tidal mixing efficiency of 2.6%.

	Percent Change in Solar Energy			
Location[1]	3	1	-1	-3
A Georges Bank				
Mixing Eff.=2.6%	5.54	1.88	-1.91	-5.80
B SW Nova Scotia				
Mixing Eff.=2.6%	6.80	2.27	-2.80	-6.87
C Eastern Maine and New Brunswick				
Mixing Eff.=2.6%	6.73	2.25	-2.26	-6.80

[1]Refer to Fig. VI-1

the nitrogen curve increases monotonically for SW Nova Scotian waters over the range of tidal energies tested.

Table VI-2 presents the model estimates of changes in pelagic fish production for the predicted increases in tidal mixing, as well as for similar decreases in tidal mixing energy. Pelagic fish yield is predicted to decrease from 2 to 4% in SW Nova Scotian waters for a 16 to 33% increase in tidal mixing energy. Table VI-3 shows that the change in pelagic fish yield (-2.8 to -6.8%) to be expected for a 1 to 3% decrease in solar energy is similar to changes produced by a 16 to 33% increase in tidal energy for SW Nova Scotia.

Eastern Maine and New Brunswick

The response of pelagic fish yield to variations in tidal energy input for eastern Maine and New Brunswick waters (Fig. VI-3c) was similar to the model response observed off SW Nova Scotia. Increased tidal energy produced a decrease in fish yield while decreased mixing caused an increase in yield, except for the largest decrease (50%) in tidal energy at the highest mixing efficiency (2.6%), which caused a decrease in fish yield. Fish yield was most sensitive to increases in tidal energy at lower mixing efficiencies.

Figure VI-4c shows that nitrogen in the water is a monotonically increasing function of tidal energy input as expected from the two previous cases. Once again nitrogen in the water column is most sensitive to changes in tidal mixing for higher mixing efficiencies.

Pelagic fish yield is predicted to decrease from 2 to 5% for the predicted 16 to 33% increase in tidal mixing (Table VI-2). This change is similar to that caused by a 1 to 3% decrease in solar radiation (Table VI-3). Table VI-2 demonstrates that for lower mixing efficiencies eastern Maine and New Brunswick waters are more sensitive than SW Nova Scotian waters to changes in tidal mixing.

DISCUSSION

Area C in Fig. VI-1 was defined with boundaries different from those of Campbell and Wroblewski(4). In the present study New Brunswick waters were included with the eastern Maine coastal waters (eastern Maine waters include both central and eastern Maine herring assessment areas) to comprise area C in Fig. VI-1. Table VI-4 shows a comparison of the long-term average herring production for areas in the Gulf of Maine region. From Table VI-4 and Fig. VI-2 it is evident that New Brunswick waters are far more productive than expected based on the light and nutrient supply to primary production in this area. The waters of eastern Maine produce somewhat less herring biomass than expected based

Table VI-4. Comparison of herring production for coastal areas of the Gulf of Maine and Georges Bank shown in Fig. VI-1. [Values compiled from Refs. 1, 6, 11.]

Location	Herring Production $g\ m^{-2}\ yr^{-1}$
New Brunswick (n=33)	15.8
SW Nova Scotia (n=27)	11.2
Georges Bank (n=21)	9.3
Central Maine (n=38)	4.3
Eastern Maine (n=38)	3.6
Western Maine (n=38)	3.4

on the energies available to support primary production from May to October. There is no reason to expect New Brunswick waters to be more productive than the waters of Georges Bank or SW Nova Scotia. Also there is no basis for assuming that energy transfers through the trophic chain will be more efficient in New Brunswick than elsehwere. Both the high New Brunswick herring production and the low eastern Maine herring production could be explained if there was a migration of herring eastward along the Maine coast. Herring tagging studies do present evidence for an eastward migration of herring along the Maine coast(5,9). New Brunswick and eastern Maine waters were combined on the basis of this evidence.

An increase in tidal mixing energy leads to more nitrogen in the water column in all cases, as expected. However, increased tidal mixing causes an increase in pelagic fish yield on Georges Bank, but a decrease in fish yield for SW Nova Scotian as well as eastern Maine and New Brunswick waters. The mechanism by which these alternate behaviors are produced was first described by Riley(31). These two opposite results can occur in the same model because there is an optimum tidal mixing energy for maximum fish production. It is therefore most important that the values for the model storages and flows are correct, since they will determine which of these two contrasting behaviors is observed. An increase in primary production and therefore in fish production with increased tidal mixing implies a nutrient limited condition, whereas, a decrease in primary production under similar conditions implies light limitation.

The mixing efficiency used here represents the tidally dissipated energy that goes into the dispersion of materials within the water column producing a net transport from areas of higher to lower concentration. At the tidal front boundary this mixing efficiency will be equal to the efficiency at which tidally dissipated energy is just able to break down the thermal stratification of the water column, determined to be 0.26%(13). For shallower waters this mixing efficiency for transport could be considerably larger. Therefore, it is represented as an order of magnitude larger than the mixing efficiency at the frontal boundary. In the model an increase in the mixing efficiency of tidal energy causes the tide to be more important relative to wind energy in mixing processes. On Georges Bank where primary production is nutrient limited a higher mixing efficiency means a larger relative increase or decrease in nutrients supplied, and therefore, the model is more sensitive to changes in tidal energy at higher mixing efficiency. For the SW Nova Scotian and eastern Maine and New Brunswick cases the increased importance of tide relative to wind in supplying nitrogen at higher mixing efficiencies causes decreases in primary production to be less severe than for lower mixing efficiencies where the positive stimulation of additional nitrogen is not as great.

Change in the primary production of tidally mixed areas is only one mechanism by which the productivity of pelagic fisheries may be altered by increased tidal mixing. Another possible

effect is that the well mixed area itself will increase in size. Garrett et al.(13) examined this possibility and found that the tidally mixed areas on Georges Bank and along SW Nova Scotia were slightly expanded. An increase in the herring stock support area could increase the size of the stock and produce a larger total fish yield.

It is possible that an increase in the land-sea temperature contrast caused by surface water temperatures lowered by increased tidal mixing could increase the incidence of fog along the already light limited coasts of SW Nova Scotia and eastern Maine and New Brunswick. If available solar radiation decreased 1% due to the increased incidence of fog, pelagic fish production would be lowered about the same amount as for a 16% increase in tidal mixing energy (Table VI-2 and VI-3). A 3% variation in solar energy input may be expected from year to year based on variable climatic conditions along the coasts of the Gulf of Maine(4). A comparison of Tables VI-2 and VI-3 shows that the variation in pelagic fish production due to normal climatic variability is slightly greater than any predicted changes from the construction of a tidal power dam. Therefore, if a tidal power dam is constructed in the upper Bay of Fundy it will probably be very difficult to detect any effects it may have on fisheries production in the Gulf of Maine and on Georges Bank.

APPENDIX VI-1

MODEL EVALUATION

The pathways, storages, and forcing functions shown in Fig. VI-2 are defined in this appendix. The appropriate symbol from Fig. VI-2 is given along with its definition and a description of how its value was calculated. Any references or assumptions necessary to obtain a value for the expression are explained.

The final values shown for Figure VI-2c were determined by a recursive procedure starting with the values given below. The model was completely evaluated and then the amount of additional nitrogen necessary to satisfy phytoplankton demands was compared to the amount of nitrogen that the available mixing energy in this area could supply, if the rate of nutrient supplied per unit of total mixing energy available was similar to the SW Nova Scotian case. All flows were reevaluated to reflect the smaller potential for nutrient supply and this process was continued until the amount of nitrogen required was less than the maximum amount that could be supplied based on the available mixing energy.

Forcing Functions

J_1 is the solar insolation at the water surface. The May to October (hereafter referred to as 0.5 yr) mean of the total possible direct plus diffuse solar radiation was calculated using formulas for an atmospheric transmission coefficient of 0.9(21). The average latitudes for Georges Bank, the SW Nova Scotia coast, and the eastern Maine and New Brunswick coast are 41.5, 43.5, and 44.5 degrees, respectively. The May to October average percent possible direct solar insolation received at Portland, Maine was 60% for the years 1941 to 1981(38). This value was applied to Georges Bank. A similar average from 1958 to 1970 at Yarmouth, NS showed that 45% of the total possible direct solar insolation was received from May to October(10). This value was used for the SW Nova Scotian coastal area and an average of the two stations used to give 53% of possible solar insolation received on the eastern Maine and New Brunswick coast. These calculations give 8.5×10^5 kcal m^{-2} $0.5yr^{-1}$ for Georges Bank, 6.7×10^5 kcal m^{-2} $0.5yr^{-1}$ for the SW Nova Scotian coast, and 7.5×10^5 kcal m^{-2} 0.5^{-1} for the eastern Maine and New Brunswick coast.

J_R is the albedo, estimated as 10% of incident solar radiation for 42 degrees north latitude(41).

J_N is the nitrogen transported into the surface waters by rain, land runoff, ocean currents and upwelling. Values for these flows are assumed to be the same for each part of the Gulf of Maine system(cf. 33). 1.8 g N m^{-2} $0.5yr^{-1}$ enter in the surface waters rounding Cape Sable, 0.1 g N m^{-2} $0.5yr^{-1}$ enters through river runoff, 0.2 g N m^{-2} $0.5yr^{-1}$ enters in rainfall, and

2.19 g N m^{-2} $0.5yr^{-1}$ is upwelled to the surface waters. Upwelling is calculated from the difference between surface water losses down the shelf and surface water inputs. The total advective addition of nitrogen is 4.3 g N m^{-2} $0.5yr^{-1}$.

N_D is the nitrogen in the deep water layer from 50 to 100 m. A value of 9.4 g N m^{-2} for the eastern Maine coast was calculated from Apollonio and Applin(2). 9 g N m^{-2} were measured in November for surface waters off Southwest Nova Scotia(24) and this value is assumed to reflect the nitrogen concentrations at depths of 50-100 m in summer. A May to October average of 8.6 g N m^{-2} from the northern and southern flanks of Georges Bank at depths 65 to 120 m is taken from Pastuszak et al.(28). An average NH_4:NO_3 ratio of 1:10 for nitrogen in Gulf of Maine waters 50 to 100 m deep was estimated from Ketchum(19). The estimates of N_D based on nitrate concentrations were increased 10% to include ammonia nitrogen.

J_T is the average tidal energy dissipated in waters shallower than 100 m except for Georges Bank where the area shallower than 60 m was used. An area weighted average(from 16) gave $7.5x10^{-5}$ w cm^{-2} or 2823 kcal m^{-2} 0.5 yr^{-1} for the area of Georges Bank <60 m in depth, $7.3x10^{-5}$ w cm^{-2} or 2748 kcal m^{-2} 0.5 yr^{-1} for the SW Scotian coast <100 m in depth, and $5.4x10^{-5}$ w cm^{-2} or 2033 kcal m^{-2} 0.5 yr^{-1} from Gran Manan to St. John, New Brunswick. Greenberg's(16) grid spacing of 22 km does not adequately resolve the Maine coast out to the 100 m isobath which is no more than 22 km wide in some places. For this reason tidal dissipation along the Maine coast was calculated using the formula from Garrett et al.(13):

$$D = (4/3\pi)\gamma \rho U^3 \qquad (1)$$

where ρ is the water density, γ is the frictional drag coefficient equal to 0.0024 and U^3 is the depth averaged tidal velocity. The depth averaged tidal velocity along the eastern Maine coast was 0.52 m s^{-1}(38) assuming zero velocity at the bottom and a linear decay of velocity from mid-depth. Vermersch et al.(40) found a depth averaged velocity of 0.038 m s^{-1} at the 100 meter contour near Monhegan Island. The average velocity over the eastern Maine coast is then 0.28 m s^{-1}. Substituting this value into equation (1) we obtain a tidal dissipation of 865 kcal m^{-2} 0.5 yr^{-1}. An area weighted average for eastern Maine and New Brunswick gave 1165 kcal m^{-2} 0.5 yr^{-1} of tidal energy dissipation.

J_W is the wind energy transferred to the water surface. Wind stress over the Gulf of Maine shallower than 100 m was taken from Saunders(32). An average of summer and fall values gave wind stresses of 0.23 dynes cm^{-2} over Georges Bank, 0.31 dynes cm^{-2} over SW Nova Scotia; and 0.46 dynes cm^{-2} over the eastern Maine coastal area. The relationship between shear stress and wind velocity is given by

$$\tau = \rho C_D(U_{10})^2 \qquad (2)$$

where ρ is the air density given a value of 1.2×10^{-3} g cm^{-3}, C_D is the drag coefficient assumed to be 1.0×10^{-3} for wind velocities around 5 m s^{-1}(35), and U_{10} is the wind velocity 10 m above the water surface.

Substituting the shear stress values given above into equation (2) we obtain an average wind velocity of 619 cm s^{-1} for the eastern coast, 438 cm s^{-1} for Georges Bank, and 500 cm s^{-1} for the area off SW Nova Scotia. Multiplying average shear stress by the average velocity gives an average available energy of 285 ergs s^{-1} cm^{-2} for the eastern coast, 101 ergs cm^{-2} for Georges Bank, and 155 ergs cm^{-2} along the SW Scotian coast. For the half year from May to October we have 1073 kcal m^{-2} 0.5 yr^{-1} available along the eastern coast, 380 kcal m^{-2} 0.5 yr^{-1} over Georges Bank, and 584 kcal m^{-2} 0.5 yr^{-1} along the SW Scotian coast.

Richman and Garrett(30) estimate that 4 to 9 percent of the available wind energy is transferred to the mixed layer. Using their average estimate or 6.5%, the values for J_W are 70 kcal m^{-2} 0.5 yr^{-1} for the eastern Maine and New Brunswick area, 25 kcal m^{-2} 0.5 yr^{-1} for Georges Bank, and 38 kcal m^{-2} 0.5 yr^{-1} for the SW Nova Scotia Coast.

E is the fishing effort which is a constant in this analysis equal to the average effort over the period from which average yield of the respective areas was calculated.

Storages

P_N is the amount of phytoplankton in the surface water. It is an instantaneous storage and therefore is listed here. P_N is calculated as the difference $(J_1-J_2-J_3)$.

R denotes the site of phytoplankton metabolic processes. It is a reminder that there is an energy cost for maintenance of the phytoplankton even though they are not explicitly included in the model.

T is the tidal kinetic energy stored in the water column. The area weighted averages of the tidal kinetic energy in the water are 0.82 j cm^{-2} for Georges Bank < 60 m in depth, 1.04 j cm^{-2} along the SW Scotian coast, and 0.24 j cm^{-2} along the eastern Maine coast(16). These values convert to 2.0 kcal m^{-2}, 2.5 kcal m^{-2}, and 0.6 kcal m^{-2}, for each area respectively.

W is the wind kinetic energy in the water column. The mean value of wind energy in the mixed layer at any given time is calculated from the average value of wind energy transferred to the mixed layer per day, J_W, with an average decay time, 1/k, of 0.42 days(20). At steady state, W approaches an asymptote of J_W/k equal to 0.16 kcal m^{-2} for the eastern coast (W in Fig. VI-

2c), 0.06 kcal m^{-2} for Georges Bank, and 0.09 kcal m^{-2} for the SW Nova Scotian coast.

Z is the biomass of macrozooplankton, microzooplankton, and protozoans(33). The total biomass in these three groups for the Gulf of Maine was 55 kcal m^{-2} and over Georges Bank the total was 35 kcal m^{-2}. The Georges Bank value is assumed to be the better approximation of zooplankton biomass in well mixed waters of the Gulf of Maine as well. Their value for the Gulf of Maine is thought to be more appropriate for the stratified deeper waters of the Gulf. The biomass values shown in Fig. VI-2 were obtained by dividing zooplankton production by an aggregated production to biomass ratio of 15. P:B ratios were assumed to be 7 and 25 for macro and microzooplankton, respectively(7) and a P:B ratio of 40 was assumed for protozoans.

F is the biomass of pelagic fish. Herring are assumed to account for 90% of pelagic fish biomass as was the case for the moderately exploited herring fishery on Georges Bank in the early sixties(34). The size of the Georges Bank stock from 1961 to 1976 was estimated as 69.6 kcal m^{-2} assuming that the area < 60 m is responsible for supporting the stock(1). The herring stock off SW Nova Scotia was estimated at 62.2 kcal m^{-2}(17). Pelagic fish biomass for eastern Maine and New Brunswick was calculated from fish yield using a P:B ratio of .3(34).

N is the nitrogen in the surface layer of water. Summer nitrate nitrogen concentrations of 3.8 g N m^{-2} were measured for the eastern Maine coastal area(2). An area weighted average of nitrate in the surface waters of Georges Bank from May to October was found to be 1.44 g N m^{-2}(28). An average of April and September stations from O'Boyle et al.(24) gives 3.8 g N m^{-2} in the surface waters off southwest Nova Scotia. We assume that ammonia is 45% of surface water nitrate concentrations(33), therefore these values are increased by 45% in Fig. VI-2.

Pathway Fluxes

$J_O=k_ON/WT$ is the solar radiation absorbed by the ecosystem, and it is calculated by the difference (J_I-J_R).

$J_I=k_INJ_R/WT$ is gross primary production. Values for the net dissolved and particulate carbon production from May to October were calculated from O'Reilly and Busch(27). The portion of Georges Bank < 60 m in depth was found to have a primary production of 2679 kcal m^{-2} 0.5 yr^{-1}. Their value of 1653 kcal m^{-2} 0.5 yr^{-1} for the Gulf of Maine was adjusted to reflect the observation that summer production of the well mixed areas is 2.5 times greater than in the stratified areas(42). Making this adjustment, there are 2850 kcal m^{-2} 0.5 yr^{-1} of primary production available to the ecosystems of eastern Maine and SW Nova Scotian coasts. Gross production was obtained by adding phytoplankton respiration equal to ten percent of net production to each value.

$J_2=k_2P_N$ is phytoplankton respiration and excretion. Respiration is estimated as 10% of net primary production(36). An average value for phytoplankton excretion of 10% was adopted(27).

$J_3k_3ZP_N$ is zooplankton ingestion. Average zooplankton production on Georges Bank was estimated at 18% of phytoplankton production(7). Estimating zooplankton production directly from phytoplankton production, J_1, gives 482 kcal m^{-2} 0.5 yr^{-1} for Georges Bank; 513 kcal m^{-2} 0.5 yr^{-1} for the eastern Maine and SW Nova Scotia coast. Zooplankton respiration and excretion account for 755 kcal m^{-2} 0.5 yr^{-1} along the coasts of eastern Maine and SW Nova Scotia, and 709 kcal m^{-2} 0.5 yr^{-1} on Georges Bank. If assimilation is equal to production plus respiration and excretion and 90% of the food ingested is assimilated then 1409 kcal m^{-2} 0.5 yr^{-1} are ingested along the coasts of eastern Maine and SW Nova Scotia, and 1323 kcal m^{-2} 0.5 yr^{-1} are ingested over Georges Bank.

$J_4=k_4ZP_N$ is zooplankton assimilation which is assumed to have a value of 90% of ingested dry weight(8). This assumption is perhaps not unreasonable since the entire size spectrum of zooplankton is included in this variable.

$J_5=k_5Z$ is zooplankton respiration and excretion. These values were obtained from the flows in J_6 by multiplying g N by C:N ratio of 6.625:1(29) to get gC and then multiplying by 10 kcal gC^{-1}(7).

$J_6=k_6Z$ is the nitrogen remineralized from zooplankton. Remineralization by macro and microzooplankton and protozoa was estimated to be 11.4 g N m^{-2} 0.5 yr^{-1} along the Maine and Nova Scotia coasts and 10.7 g N m^{-2} 0.5 yr^{-1} over Georges Bank(cf. 33).

$J_7=k_7ZF$ is ingestion by pelagic fish. Sissenwine et al.(34) estimated that pelagic fish on Georges Bank in the mid-sixties consumed 4.5 times their biomass and 15 times their production. If fish consume 75% of their nutritional requirements from May to October, an estimation of ingestion from stock size gives 233 kcal m^{-2} 0.5 yr^{-1} along SW Nova Scotian coast, 260 kcal m^{-2} 0.5 yr^{-1} over Georges Bank, and 98 kcal m^{-2} 0.5 yr^{-1} along the eastern Maine and New Brunswick coast.

$J_8=k_8ZF$ is assimilation of pelagic fish. We assumed an assimilation for herring of 90%(3).

$J_9=k_9F$ is fish respiration, excretion and natural mortality, and was calculated as the difference (J_8-J_{11}).

$J_{10}=k_{10}F$ is remineralization from fish and is calculated from J_9 using a C:N ratio of 6.625:1.

$J_{11}=k_{11}FE$ is harvest of pelagic fish. Herring catch data were taken from refs. 1, 9 and 11. The average yield of area C in Fig. VI-1 was 8.7 kcal m^{-2} yr^{-1} based on 38 years of data from the central and eastern Maine coastal fisheries and 33 years of data from New Brunswick. The average yield of the Nova Scotian (n=27) fishery was 14 kcal m^{-2} yr^{-1}. The average yield (n=21) for the Georges Bank fishery was 11.6 kcal m^{-2} yr^{-1}. Herring yield is assumed to comprise 90% of pelagic fish yield.

$J_{12}=k_{12}P_N$ is remineralization from phytoplankton, and was calculated from J_2 using a C:N ratio of 6.625:1.

$J_{13}=k_{13}T(N_D-N)$ is the nitrogen input to the mixed layer from tidal mixing. The nitrogen necessary to support the observed primary production and not supplied by recycling or advection is assumed to come from the net transport of vertical and/or horizontal mixing driven by the wind and tide. The amount of nitrogen input due to the tide is prorated by the ratio $J_{18}/(J_{18}+J_{20})$. Energy from either source is assumed to be equally effective at mixing nutrients into the surface layer.

$J_{14}=k_{14}N$ is the advective nitrogen loss down the shelf and was taken as 2.9 g N m^{-2} 0.5 yr^{-1}(33).

$J_{15}=k_{15}NJ_R/WT$ is the nitrogen requirement of the phytoplankton which is found from J_1 by dividing by 11.4 kcal gC^{-1}(7) and 6.625 g N g C^{-1}.

$J_{16}=k_{16}W(N_D-N)$ is the nitrogen input to the mixed layer from wind mixing. This value is calculated as in J_{13}, but it is prorated as the ratio $J_{20}/(J_{18}+J_{20})$.

$J_{17}=k_{17}T$ is the tidal energy dissipated in processes other than mixing, and it is calculated by the difference (J_T-J_{18}).

$J_{18}=k_{18}T(N_D-N)$ is the tidal energy used in mixing. Garrett et al.(13) calculated a mixing efficiency of 0.26% at the frontal boundary. Garrett's mixing efficiency refers to the amount of energy that goes into breaking down the thermal stratification of the water column. This mixing efficiency is only equal to the mixing efficiency for transport at the frontal boundary. It seems logical to assume that more tidal energy will go into vertical transport of materials within the water column where the gradient is less or the depth shallower. The model is run for several values of the mixing efficiency but the evaluations in Fig. VI-2 are shown for 0.26%.

$J_{19}=k_{19}W$ is the wind energy dissipated in processes other than tidal mixing, and it is calculated by the difference (J_W-J_{20}).

$J_{20}=k_{20}W(N_D-N)$ is the wind energy used in mixing. Richman and Garrett(30 - using data from 18) estimate that 6 to 8% of the energy transferred to the mixed layer goes into vertical mixing. Using a value of 7%, the energy which goes into vertical mixing

is 4.9 kcal m^{-2} 0.5 yr^{-1} for the eastern Maine and New Brunswick coast, 1.8 kcal m^{-2} 0.5 yr^{-1} for Georges Bank, and 2.7 kcal m^{-2} 0.5 yr^{-1} for the SW Nova Scotian coast.

J_{21} is the amount of zooplankton production that is available to predators other than pelagic fish.

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VII. SEA LEVEL CHANGE AND OCEAN CLIMATE: ITS EFFECT ON FISHERIES RESOURCES IN THE BAY OF FUNDY AND GULF OF MAINE

M. J. Dadswell and R. A. Rulifson

INTRODUCTION

The Bay of Fundy-Gulf of Maine system is important to many commercial and recreational fisheries of the Northwest Atlantic. At least 43 fish species inhabit tideflat waters of the upper Bay of Fundy(6), many of which support important commercial fisheries throughout the Bay of Fundy-Gulf of Maine region (Table VII-1). Some of the more valuable and abundant fish species in the upper Bay include Atlantic salmon (Salmo salar), American shad (Alosa sapidissima), Atlantic herring (Clupea harengus), mackerel (Scomber scombrus), striped bass (Morone saxatilis). In the outer Bay of Fundy and Gulf of Maine, major fisheries exist for lobster (Homarus americanus), scallop (Placopecten magellanicus), herring (Clupea harengus), cod (Gadus morhua) and haddock (Melanogrammus aeglefinus).

The purpose of this paper is: (1) to summarize the possible effects of sea-level rise presented by thematic session speakers; (2) to present an overview of the more valuable commercial fisheries in the region and methodologies of capture; and (3) to suggest recommendations for future activities predicting effects of sea-level rise on fishery resources in the Bay of Fundy and Gulf of Maine. The effects on fisheries caused by tidal power developments have been explored elsewhere(5,7).

GENERAL EFFECTS OF SEA-LEVEL RISE

Sea level has been rising since the last ice age, approximately 20,000 years ago, when the shore was near the present shelf break(12). Changes in the shoreline since that time have been due to crustal warping, subsidence of landmasses, and glacial melting. The nodal tidal cycle of 18.61 years(18), combined with the potential problems associated with the greenhouse effect(15,21) and tidal-power development in the Maritime provinces will produce further physical changes in the Gulf of Maine-Bay of Fundy system that may have beneficial or detrimental effects on fish stocks of the region.

Table VII-1. Commercially-important fish species caught in Bay of Fundy waters and landed at USA ports during the years 1963-1978. Landings given in metric tons. Data from NOAA, National Marine Fisheries Service, Resource Statistics Division.

Species group	Year 1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
Anglerfish													0.14		0.23	0.05
Atl. cod - all	350.99	227.34	410.27	385.60	848.40	449.83	107.23	136.62	97.07	89.85	4.90	52.35	50.89	77.84	83.60	4.86
Cusk	11.93	20.68	23.31	28.12	22.32	10.39	1.13	8.12	11.79	2.36	1.72	3.18	2.31	2.95	2.68	0.09
Flounder -																
Blackback	5.94	3.04	0.41	0.09	5.53	2.00	0.18	0.36	0.05						0.09	
Sea Dab	28.94	83.14	133.58	64.50	107.37	28.53	22.68	24.27	58.69	21.00	0.77	3.81	1.68	4.76	3.81	0.73
Gray sole	16.51	40.14	41.87	14.15	71.30	20.82	9.25	24.36	31.12	22.59	1.77	25.22	2.00	4.44	2.95	0.27
Lemon sole	0.18	2.00			0.54	0.05		0.23	0.77							
Yellowtail	1.63	0.95	2.40	5.17	12.93	5.94	3.76	4.58	0.91					0.64	0.09	
Haddock	1325.44	1032.15	1771.68	1294.37	2505.05	690.87	194.59	167.60	142.93	64.41	1.59	21.68	43.41	82.15	66.36	17.92
Hake -																
Red	2.72														0.18	
White	154.72	103.56	100.02	56.70	139.98	64.50	27.99	34.61	48.17	60.33	4.90	29.39	14.42	21.32	19.82	0.95
Halibut	1.04	1.32	2.81	1.36	2.22	2.27	0.91	0.86	0.32	0.64	0.18	0.18	0.27		0.14	
Ocean perch	89.49	60.74	72.03	18.55	43.91	35.74	11.48	48.08	27.26	18.51	0.54	18.82	52.71	23.31	13.93	5.08
Pollock	342.73	172.00	68.04	134.44	87.23	48.44	67.81	98.93	24.40	99.20	6.94	78.15	57.97	56.61	46.99	1.32
Sharks	0.09		0.27											0.05		
Skates		0.05			0.23											
Whiting	0.95	0.32		0.09	0.54			0.54							7.67	
Wolffish	4.94	11.29	3.40	3.08	6.89	2.00	1.18	1.81	1.09	2.09	0.09	0.59	0.59	0.50	0.36	0.09
Uncl. finfish	0.18	0.68	2.27					0.32							0.05	
Squid			0.23													
Total tonnage	2338.42	1758.72	2631.00	2008.49	3854.44	1361.38	448.19	551.34	444.57	380.98	23.40	233.37	226.39	274.57	248.95	31.36
Total value (US (dollars x 1000)	427.0	342.8	681.6	448.8	868.9	292.1	123.9	194.0	192.2	144.1	985.4	99.2	103.5	190.6	175.3	29.7

Rise in sea level will result in increased tidal amplitude, which will increase water circulation and vertical mixing (Fig. VII-1). The cooler, nutrient-rich bottom waters will be brought to the surface by upwelling, causing a decrease in sea-surface temperature and increases in nutrient recirculation and primary productivity.

Historical catch data(8,20) show that some fish stocks are affected by changes in ocean temperatures. Lower sea-surface temperatures resulting from upwelling may decrease the abundance and occasional occurrence of southern finfish species which are now at the northern limit of their range. Examples of these species include menhaden (Brevoortia tyrannus), bluefish (Pomatomus saltatrix), alewife (Alosa pseudoharengus), and butterfish (Poronotus eriacanthus). Pelagic fish species, such as the Atlantic herring, which show positive correlations of abundance with changes in sea-surface temperature, will most likely exhibit decreased stock size in the Bay of Fundy-Gulf of Maine complex(1). Species near the southern limit of their range (cod, halibut, pollock, cusk) typically show a negative correlation of abundance with sea-surface temperature; stocks of these species may increase in abundance with sea-level rise. Some fish stocks will not exhibit detectable shifts in abundance as a result of lower sea-surface temperatures.

Temperature changes may also alter migration patterns of migratory species by changing migratory cues. Increased turbulence and vertical mixing from sea-level rise may alter formation of isotherms, and the upper range of temperatures may be restricted. For example, a particular species cueing on a 17^{o}C isotherm for guidance during migration may find that the isotherm is nonexistent or has shifted in occurrence to other areas of the region, thereby restricting migratory movements within the Bay of Fundy-Gulf of Maine.

Changes in ocean circulation patterns in the Gulf of Maine and Bay of Fundy due to sea-level rise and tidal-power development may also affect fish migrations. Pelagic fishes utilizing Gulf and Bay currents as migratory cues may alter migration patterns, thereby shifting centers of abundance to other areas. Increased circulation may alter larval fish survival due to changes in food abundance or changes in distribution associated with pelagic transport.

Predicting general changes in the distribution and abundance of fish stocks in the Bay of Fundy-Gulf of Maine system due to changes in sea level is difficult. What may be a detrimental effect for one species may enhance abundance for another species. In the next section, we discuss several of the more commercially-important fish stocks and the harvest methods for each. Predictions of sea-level rise effects on fish stocks are made for each species.

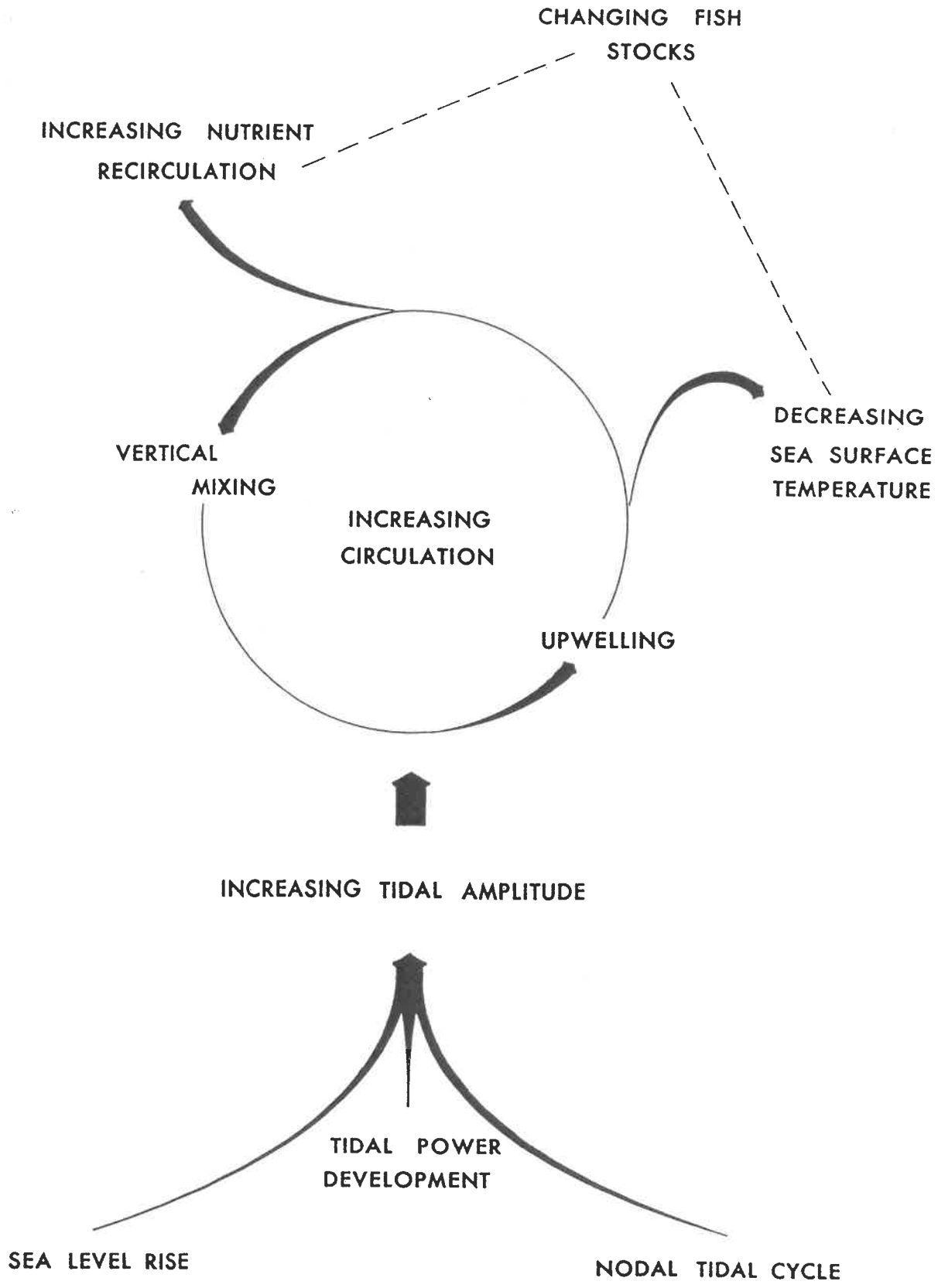

Fig. VII-1. Hypothetical interaction of sea level change, tidal cycles, circulation and fish stocks.

FISHERIES AND IMPACTS

Fisheries resources of the Bay of Fundy - Gulf of Maine - Georges Bank complex support a large and diverse fishery in Canada, the United States and, through international agreements, several foreign countries (USSR, Spain, Germany, etc.). Although a large number of fish and shellfish are exploited, landings are dominated by a few species (Table VII-2).

Lobster (Homarus americanus) and scallop (Placopecten magellanicus) are the two most valuable species. Combined they represent less than 5% of annual landings by weight, but contribute over 50% of the value of the fishery. Scallop fisheries are concentrated in the Bay of Fundy, along the Maine coast and on Georges Bank(13). The majority of landings are made by large vessels fishing on Georges Bank. Lobsters are fished out of every small port over the entire coastline of the region and offshore on Browns and Georges Banks. The majority of landings are made by vessels under 16 m.

Shrimp (Pandalus borealis) are fished in the deep southern portion of the Gulf of Maine in summer and inshore from Maine to New Brunswick in winter. Although landings have been poor lately, recent assessments indicate the stock has rebuilt and will provide good landings in the near future. Landings are predominately on the Maine coast but during its last cycle of abundance, valuable landings of shrimp were made in southwest New Brunswick(14).

The remaining invertebrate fisheries are based on resources in the intertidal zone. Marine worms (Glycera, Nereis), softshell clam (Mya arenaria) and hardshell clam or quahog (Mercenaria) are all dug from tide flats using labor-intensive methods. The fisheries for marine worms and hardshell clam are almost totally concentrated on the Maine coast. Annual landed value of marine worms often has equaled or exceeded that of lobsters in Maine(9).

A traditional fishery of the Gulf of Maine region is that for herring (Clupea harengus). This species is exploited by both fixed (weirs) and mobile (gillnets, purse seine) gear. Herring support the greatest landings by weight for the region (Table VII-2). The majority of the world's canned sardines are provided by this fishery.

Cod (Gadus morhua), haddock (Melanogrammus aeglefinus) and pollock (Pollachius virens) are widely distributed throughout the region(13). All are fished with gillnets or by trawlers and are commonly captured together. Major concentrations of haddock occur on Georges and Browns Banks, and of pollock in the southern Gulf of Maine where they support large seasonal fisheries. Cod are more generally distributed and are caught in most areas throughout the year.

TABLE VII-2. Landings and values of some important commercial species from the outer Bay of Fundy - Gulf of Maine Region, NAFO 4X, and 5Y

	Canada 1984		USA 1983	
Species	kg x 10^3	$ x 10^3	kg x 10^3	$ x 10^3
Lobster	8381	64,767	10319	79,743
Scallops (meats)	3433	41,981	7453	91,140
Shrimp	0	0	1572	2,358
Soft-shell clam	3618	3,178	1884	7,249
Quahog	0	0	-	-
Marine worms	0	0	229	3,630
Herring	81589	10,691	23000	3,013
Cod	58490	25,042	13867	5,937
Haddock	25527	19,139	5593	4,193
Pollock	28789	6,965	7377	1,785
		$174,763		$199,048

Except for the more or less sedentary molluscs and worms, all species are strongly migratory(13). Although the role that migration plays in the life history of lobsters is unproven to date, this species makes extensive movements from Maine to the Bay of Fundy and back and from Georges Bank inshore and return(4). Herring migrate throughout the region on a seasonal cycle which appears to be largely related to reproduction needs(17). Inshore fixed gear (weirs) for juvenile herring are concentrated in bays and estuaries. These are summer fisheries and movement of herring appears to be for feeding purposes and related to local current structures(16). Cod, haddock and pollock all exhibit an inshore movement in summer and offshore in winter(19). The general movement appears to be in a counter clockwise direction around the Gulf of Maine - Bay of Fundy (Fig. VII-2). All three concentrate over the offshore banks in winter for spawning.

High-tide data both from historical measurements and recent tide-level measurements indicate the Gulf of Maine region is subsiding at a rate of 30 cm per century. This submergence is due to subsidence of the earth's crust in this region as a former glacier - marginal buige collapses. In the Bay of Fundy, an additional factor has been the amplification of tidal range as a world-wide rise of sea level widened and deepened the entrance and optimized basin geometry(11). The overall effect of increased tides and sea level in the region has been to lower the mean annual sea temperature. During the last 6000-8000 years, species composition has changed from warm-temperate to cool-temperate(2). Annual ocean temperature, because of the large-scale tidal mixing and lack of stratification in the Gulf of Maine complex, is under the strong influence of the 18.6 year nodal tidal cycle(18). Mean temperatures in the Bay of Fundy are 1-2^{o}C higher at present than they were during the mid-1960's (Fig. VII-3). As sea levels increase in the future, either for natural or anthropogenic reasons, we should expect a lowering of mean annual temperature unless current increases in atmospheric CO_2 cause global warming(3). Increased sea level and the tidal-power development effect of shortening the Bay of Fundy will both cause an increase in currents and mixing.

Effects on fisheries of decreased mean annual temperature and increased mixing in our region will be difficult to assess. However, we should expect that decreased temperatures will decrease annual production of warm water species such as lobster, worms, quahog and softshell clam. In districts with stable fisheries in terms of catch-effort, warming and cooling trends are evident in the landings for lobsters which increase during warming trends and decrease during cooling trends(9, cf. Fig. VII-4). On the other hand, cold water species such as shrimp and scallops may increase production and expand their distribution. It is questionable whether any direct effect will be observable among the finfish species since the landings of these are so subject to effort and are now controlled by quotas. The Quoddy region may experience increased herring weir catches in the short term. The data for this fishery indicates good positive

SURFACE WATER TEMPERATURES AT ST.-ANDREWS, N.-B. FROM 1921 TO 1980

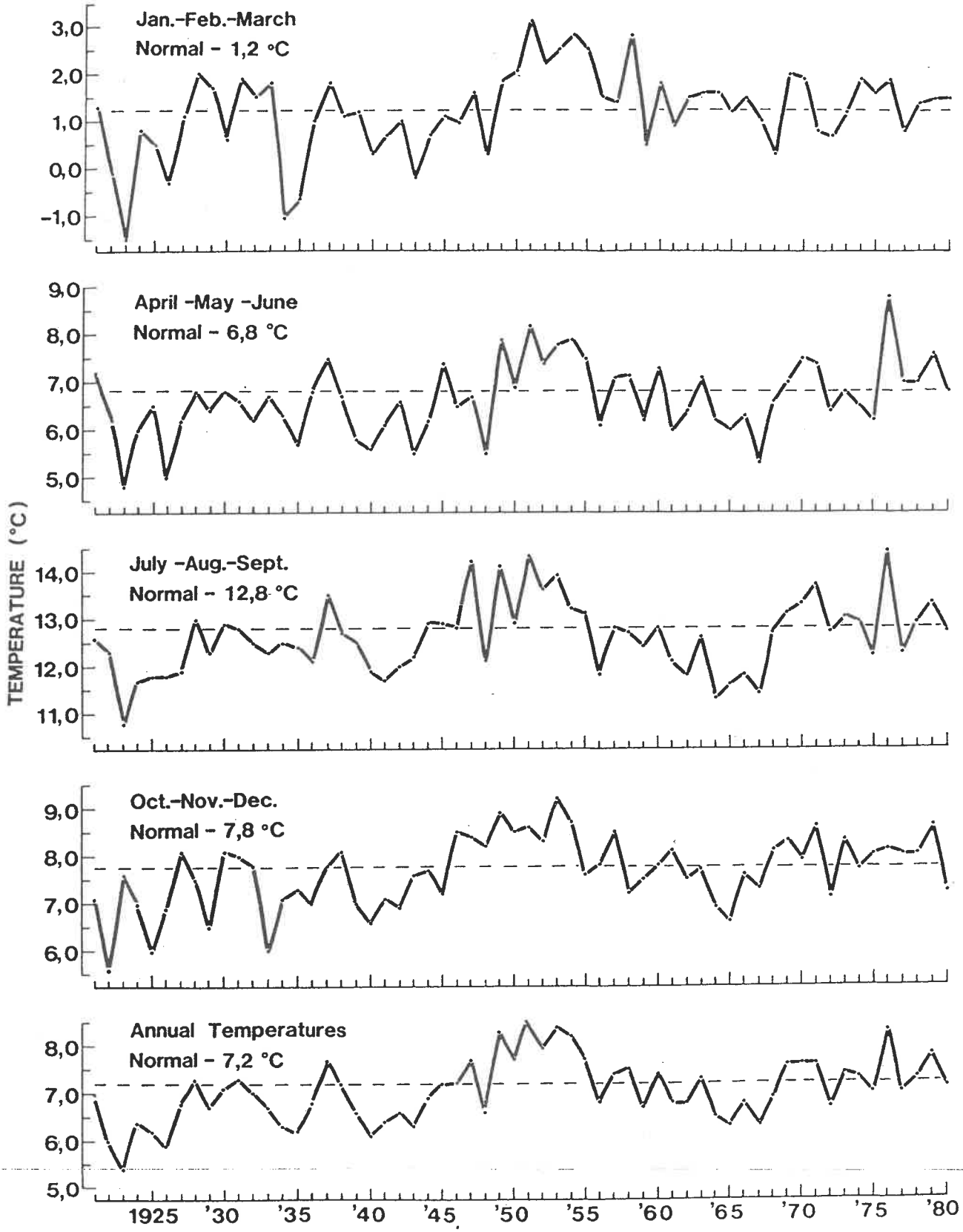

Fig. VII-2. Annual temperature variation of the Bay of Fundy 1921-1980.

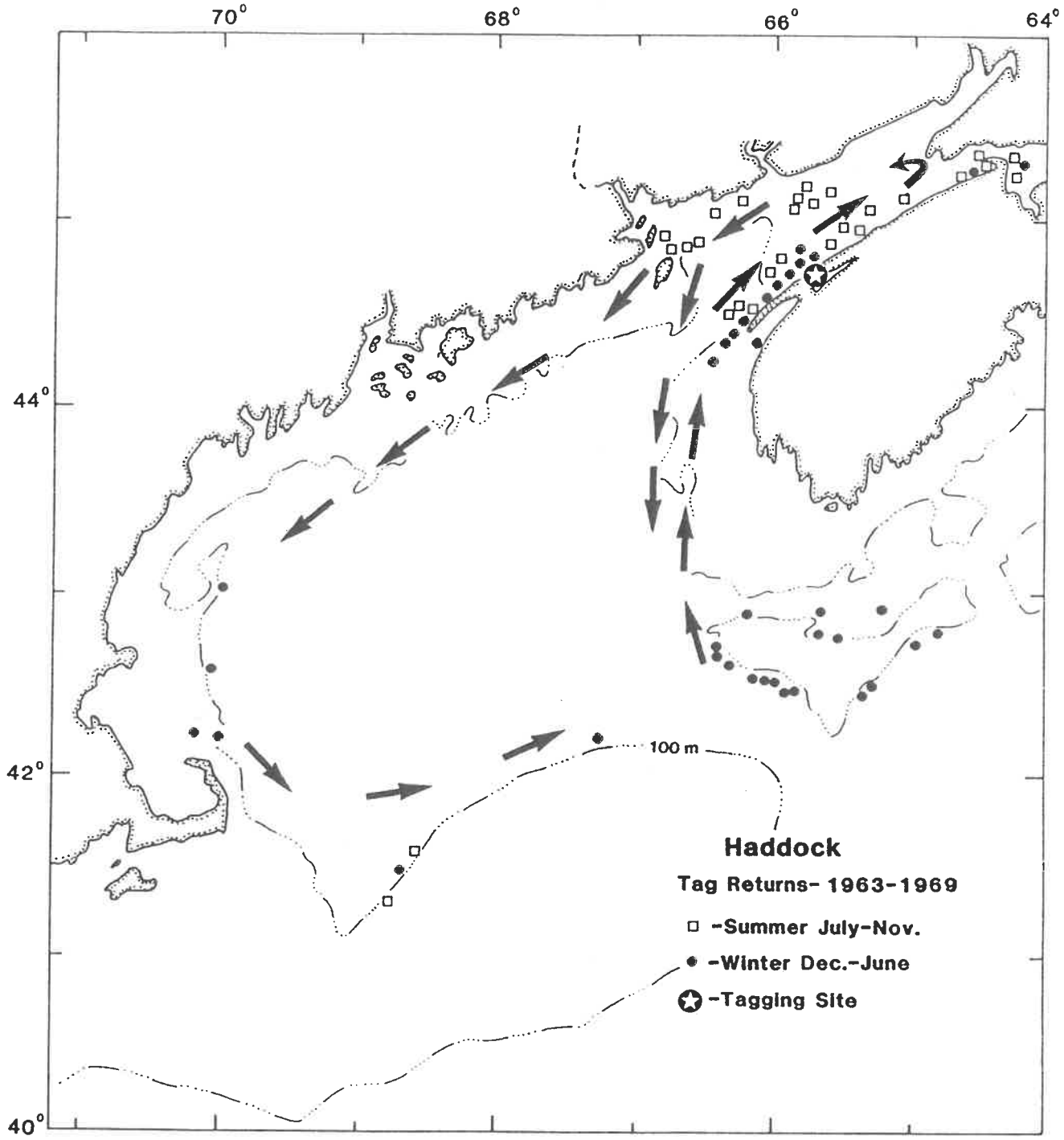

Fig. VII-3. Tag return locations for haddock (Melanogrammus aeglefinus) released at Digby, N.S., and inferred migration pathway.

correlation to the nodal cycle(8) supporting Huntsman's hypothesis that increased tides bring more herring into this region to be caught by the fixed gear.

It will be extremely difficult to predict accurately the effect change in sea level might have on fisheries. Since there is so much clutter in the environmental signal due to the interaction of various natural physical cycles, they will tend to mask each other. This is compounded by the rapid changes in fishing methods and effort brought on by technology and demand, and the continued inaccuracies of statistical reporting now compounded by the imposition of quotas. At best, if sea-level change and world climate do not counteract each other, we may see a general rise in fisheries production but a decrease in value because of reduced lobster landings.

RECOMMENDATIONS FOR FUTURE ACTIVITIES

Future research activities focused on predicting effects of sea-level rise on Gulf of Maine-Bay of Fundy fish stocks can be initiated utilizing available historical catch records and sea-surface temperature information. Several of the recommendations listed below have been initiated for certain species; examples of these studies are listed where appropriate.

We recommend that:

1) Available catch data should be compiled and analyzed to depict historical trends in abundance and distribution of Fundy-Gulf of Maine fishes. These analyses should be performed on individual species and encompass those species of commercial and recreational importance, as well as the forage-base species. Landings data compiled by the U.S. National Marine Fisheries Service and the Canadian Department of Fisheries and Oceans could be accessed for this purpose.

2) These historical trends in catch should be correlated with historical changes in sea-level rise, sea-surface temperature, turbidity, and other environmental variables. Examples are studies by Sutcliffe et al.(20)., Anthony and Fogarty(1), and DeWolfe and Daborn(8).

3) These correlations should be utilized to formulate hypotheses about species occurrence and stock size in relation to future sea-level rise.

4) Monitoring of stocks and environmental variables should be continued to enlarge the data base.

5) In the case of tidal-power development, a commission, board, or panel of experts should be established to oversee and coordinate data collection, make recommendations, and assist in formulating management policies.

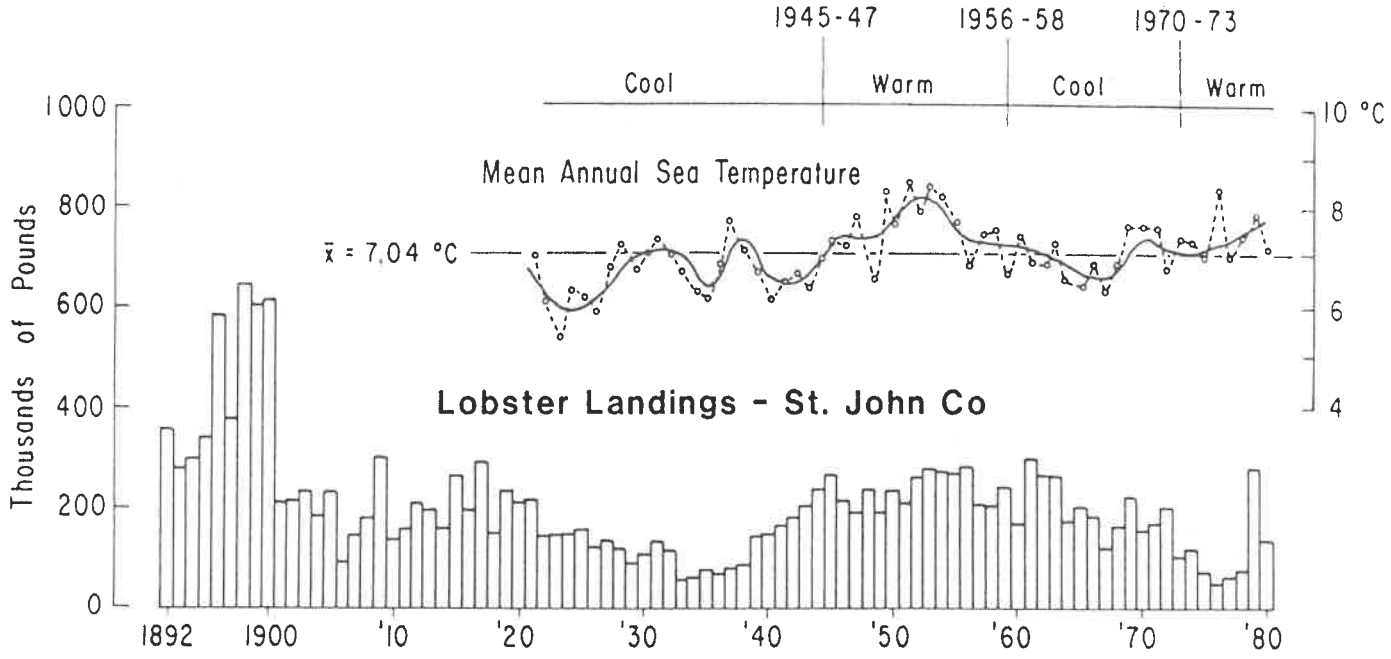

Fig. VII-4. Lobster landings in Saint John Co., N.B. 1892-1980 and mean annual sea temperature.

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ADDENDUM

A SEA-LEVEL SCENARIO FOR MINAS BASIN

J.S. Bleakney

Amos(1) calculated rising sea-level curves for Minas Basin from a series of dated, high-water marsh horizons and from extrapolated mean sea levels. He lacked information for complementary low-water positions. He concluded that the progressive inundation in Minas Basin was a function partly of an increase in tidal range (50%) and partly of a rise in apparent mean sea level (50%). Consequently, low water levels remained static.

Biological evidence, however, indicates that low-water levels have been receding in recent millenia. This can be accommodated within Amos' general thesis by assuming that the rate of rise of mean sea level has recently slowed. In combination with ever-increasing tidal amplitudes, this would have generated progressively lower tidal levels in recent times (Fig. A1). Thus, whereas sea level rise in most areas assumes that high water, mean sea level and low water rise in conjunction with one another, the effects of accelerated evolution of megatidal amplitudes in Minas Basin, superposed on mean sea level rise, resulted in depression of low-water limits to below the level of the Zirfaea of 400 yrs B.P., and even below a 3800 yrs B.P. oyster bed. The in situ remains of an extensive bed of oysters, Crassostrea virginica, which were growing under subtidal or extreme low water conditions about 3800 yrs B.P., are now 1.5-2.0 m above extreme low water(2).

The great piddock, Zirfaea crispata, a rock-boring clam, is common at Cape Blomidon, Minas Basin. Because the sturdy valves remain entrapped in their rock chambers for hundreds of years, radio-carbon dating of shell valves from old burrows is a means of deciphering fluctuations in sea levels. The upper limit of this species is at or very near extreme low water. Even though the upper limit of Zirfaea would have been more restricted 3800 years ago because of the lesser tidal amplitudes of that period, this species should nevertheless have ranged at least as high as the oysters, or nearly 2 m higher than present extreme low-water level (ELWL) at Cape Blomidon. However, the oldest evident Zirfaea burrows lie at about 140 cm above present ELWL(3) or about 60 cm below the 3800 yrs B.P. oyster level. What was the

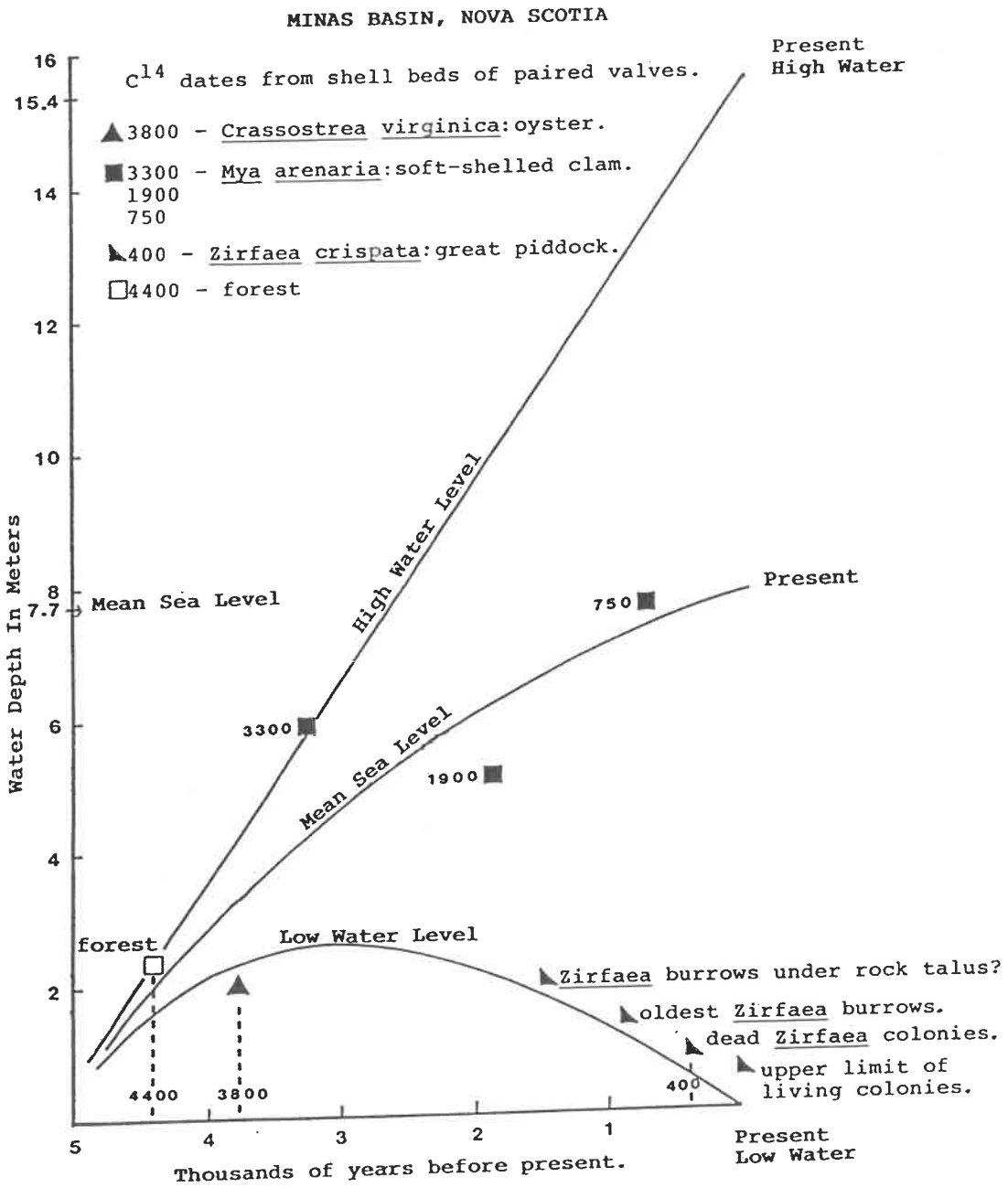

Fig. A-1. Evolution of tidal range and mean sea level in Minas Basin, Nova Scotia.

eventual upper limit of low water in Minas Basin before it began to recede? How recently did that reversal take place? The answer to both questions (via C^{14} dating) may lie beneath a talus slope of basalt rocks which has buried a portion of the shale terraces and thus protected the oldest Zirfaea burrows from erosion.

Because soft-shelled clams, Mya arenaria, occur over much of the intertidal zone, and to a depth of 9 m subtidally, they are unsuitable as precise indicators of upper and lower tidal limits. Nevertheless, three ancient Mya beds of paired valves that have been radio-carbon dated are of real interest. The oldest bed indicates that high water level exceeded that particular shell bed elevation by 3310 ± 60 yrs B.P. (Fig. A1). Both that bed and a second site dated at 1890 ± 50 yrs B.P. are located more than 1 km offshore north of Evangeline Beach, and appear to have had a depositional overburden of at least 1 - 2m. A relatively new river channel draining across the tidal flats has removed this thin cover(2). In contrast, another more recent Mya bed near Wolfville (750 ± 50 yrs B.P.) is halfway up the steep bank of the Cornwallis River and has an overburden 6 m in thickness. The nearly 12 m of layered deposit exposed along this river bank may represent more than 1500 years of deposition. This implies a dynamic system of erosion and transport, presumably associated with megatidal conditions, yet a mere 8 km to the northeast 3800 year old oysters and 4400 year old trees have a covering of only 1 or 2 m. Tidal and residual currents at Cape Blomidon, 14 km to the north of the oysters, have removed all soft deposits from the shale bedrock, and, judging from extracted Zirfaea valves dated 210, 380, 485 and 865 years old, these conditions have long prevailed because Zirfaea is easily suffocated by silty deposits.

Undoubtedly, there are additional ancient forests and shell beds in Minas Basin and the upper Bay of Fundy yet to be discovered that could contribute further to an understanding of the interaction of sea-level changes and recent megatidal evolution.

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CONTRIBUTED PAPERS

Kelley, J.T. (Maine Geological Survey, Augusta, ME 04333). ESTUARINE SEDIMENT DISPERSAL DURING HOLOCENE SEA LEVEL CHANGES IN MAINE.

Holocene sea level excursions have drowned the Maine coast to a depth of 75 m and exposed the present nearshore to a depth of 65 m. At present sea level appears to rise unevenly along the coast at rates ranging from 1 mm/yr to 9 mm/yr due to crustal warping. Throughout these sea level changes glacial sediment has been constantly reworked and moved "downhill." During the early drowning, 13,000 years ago, preglacial river valleys were blocked with sediment resulting in today's deranged drainage. During the sea level lowstand, 9,000 years ago, sediment was flushed out of estuaries into the Gulf of Maine. Today some sediment leaks out of estuaries while much is trapped behind river dams. Most sediment accumulating in modern coastal embayments is derived from eroding bluffs of glacial material.

Fink, L.K., Jr. (Univ. of Maine, Orono, ME 04573). MAINE BEACH MORPHODYNAMICS: COMPARATIVE EFFECTS OF INCREASED TIDAL RANGE AND VARIABILITY OF NATURAL EVENTS.

With an increased tidal range predicted for the Gulf of Maine because of the Fundy tidal dam, significant recession of Maine's beaches has been indicated. Presumably, this would result from an increase in the probability of occurrence of storms on a higher tide position. This study has determined the degree of change of shoreline position resulting from seasonal, secular, and Holocene changes in the elevation of mean sea level, all in light of current knowledge of Maine beach morphodynamics. Data from tide gauge stations in Portland and Eastport, specific storm events, anomalous extreme tide events, and shoreline change maps were used in this analysis of the probable response of beaches to an increased tidal range in the Gulf of Maine. Measurable changes in unstabilized shorelines have been linked to variability of MSL elevations. Unstabilized shorelines show a historical recession rate of 20-70 cm/yr while stabilized beaches show redistribution of sediment by loss of intertidal sand volume and accretion along other portions. During this time (1912-1980), there was a significant seasonal increase of 14 cm in the elevation of mean sea level between January and June, corresponding to annual peak runoff periods. The secular trend of MSL shows an average rate of rise of 23 cm/100y; a rate significantly greater than the Holocene average rise rate of 4-6 cm/100y. It is concluded that shoreline positions for

unstabilized beaches will not be changed measurably by an increase in tidal range since the existing seasonal and secular changes in mean sea level elevation and storms will continue to dominate beach responses and shoreline variability.

Loder, T.C. (Earth Sciences), C. Vorosmarty (Complex Systems Research Center), F.Short (Jackson Estuarine Lab), N. Kinner (Civil Engineering) and J. Spiller (Complex Systems Research Center, UNH, Durham, NH 03824). SPRING - NEAP TIDAL EFFECTS ON NITROGEN-PHOSPHOROUS RELATIONSHIPS IN A NEW ENGLAND SALT MARSH ESTUARY.
Samples for ammonium, nitrate plus nitrite, total dissolved nitrogen, phosphate and salinity have been collected over 14 and 26 hour time periods in the Parker River Estuary (northern Massachusetts). During spring tides marsh water floods the entire marsh surface, whereas during neap tides it remains in the marsh channels. For spring-neap comparison studies both during the summer and fall, all nutrients measured were found in significantly higher concentrations (1.5 to 3x) during the neaps for water of the same salinity. Although the total N:P ratios remained about the same, they decrease linearly with the increasing salinity gradient from 0 to 25 ppt. Possible mechanisms controlling these differences and their implications will be presented.

Batdorf, C.A. (Mass. Audubon Society, Gloucester, MA 01930). GLOUCESTER HARBOR MONITORING PROGRAM.
Benthic cores from 0, 3.5, and 7 ft intertidal levels have been collected within Gloucester Harbor, MA for the past three years as part of an ongoing monitoring program of water quality in the harbor. Statistical analyses of similarity matrices on these data are used as a form of interpreting shifts within the benthic community. These analyses show that populations change significantly quarterly and sometimes more often. The changes are probably due to seasonal community shifts, but may indicate an impact from the start-up of the primary sewage treatment plant.

Bousfield, E.L. (National Museum of Canada). BIOGEOGRAPHICAL FEATURES OF THE MACROINVERTEBRATE BENTHOS OF GEORGES BANK.
Georges Bank is a prominent physiographic feature of the North American continental shelf that defines most of the seaward boundary of the Gulf of Maine. This study reviews the principal biogeographic features of the bottom-dwelling macroinvertebrates (mainly decapod, amphipod, and mysid crustaceans, and mollusks) of the Banks region, in depths to 200 m. The Banks fauna consists of dominant northern cold-water elements that extend southwards beyond the region, some reaching a <u>southern</u> limit in the northeast portion ("corner") of the Bank proper, and a lesser southern warm-water fauna, elements of which reach their <u>northern</u> limit at the northeast portion. The possible significance of this natural faunal demarcation line with respect to commercial fishing areas of the Banks region is briefly discussed.

Gratto, G.W. and M.L.H. Thomas (Univ. of New Brunswick, Saint John). PREDATION AND PREY PRODUCTION ON AN INTERTIDAL FLAT ON THE BAY OF FUNDY.
In the Bay of Fundy, the amphipod Corophium volutator is the dominant food of benthic-feeding fish as well as the high concentrations of migratory sandpipers passing through the region. In May 1981, a study of the rates of exploitation of C. volutator was initiated at Musquash Harbour on the outer Bay of Fundy. The production of C. volutator was relatively stable over a three year period at 8.8, 9.5 and 10.6g dw/m^2/yr. All fish species combined consumed less than 1% of the annual production by C. volutator. Even though present for only an eight week period, sandpipers were by far the most important predator, consuming about 10% of the annual production. Potential invertebrate predators were rare at Musquash with only Crangon septemspinosa occurring in sufficient numbers to have a measureable impact on C. volutator.

Rangeley, R.W. and M.L.H. Thomas (Univ. of New Brunswick, Saint John). POPULATION DYNAMICS OF THE ROCK BARNACLE, Semibalanus (= Balanus) balanoides.
Population characteristics of Semibalanus balanoides and the barnacles' major predators, Nucella lapillus and juvenile Carcinus maenas, are currently being investigated on an outer western Bay of Fundy rocky shore. Barnacle shell morphology, biomass, fecundity, larval settlement and adult and juvenile summer mortality were examined in an attempt to predict larval production available to pelagic food webs. Depending upon habitat type, larval production ranged from approximately 5 to 45 g m^{-2} of dry biomass of which less than 0.3% returns to the shore in the form of cyprid settlement.

Gardner, J.P.A. and M.L.H. Thomas (Division of Sciences, Univ. of New Brunswick, Saint John). ASPECTS OF THE GROWTH OF TWO SPECIES OF INTERTIDAL MUSSELS.
A study of the growth of the Mytilidae spp Modiolus modiolus and Mytilus edulis at Welch Cove, N.B., was undertaken to relate growth to known climatic conditions, to food availability as well as to space. Analysis of the water at high tide over the mussel beds indicates that food availability is relatively great, whilst potential ration of the rock pools at low tide has been shown to decrease considerably in a 3 hr. period of mussel feeding activity. Whether growth and production is limited at low tide due to a depletion of food immediately above the mussel beds is still unclear. The ability of mussels to induce mixing of the water to a degree whereby food availability is increased was investigated. The combined effects of temperature plus salinity upon the feeding rate of rock pool mussels were investigated to determine how variation of those two factors during the tidal cycle might affect growth.

Brylinsky, M. (Dept. of Biology, Acadia University, Wolfville, N.S.). PHYTOPLANKTON PRIMARY PRODUCTION IN THE SOUTHERN BIGHT OF THE MINAS BASIN.
In situ measurements of phytoplankton primary production using

both carbon-14 and oxygen production techniques were made during the 1985 growing season. Production rates appear to be primarily a function of the availability of solar radiation and can be predicted quite well from a knowledge of incident light flux and euphotic zone depth. The latter is a function of SPM concentration which is in turn related to tidal state. There is no indication that nutrients are ever limiting.

Cranford, P.J. and P. Schwinghamer (Bedford Institute of Oceanography, Dartmouth, N.S.). IDENTIFICATION OF SPARTINA-DERIVED DETRITUS IN BAY OF FUNDY SUSPENDED MATTER.
A histochemical staining technique has been developed which differentiates Spartina-derived detritus from other material in the suspended matter fraction of water samples collected in the upper reaches of the Bay of Fundy. The method has been used to help determine the origin of particulate matter gathered along the axis of the Cumberland Basin in March 1985 and in the water flooding the Grand Pre saltmarsh over a seasonal cycle in 1983. The results confirm earlier observations that Spartina-derived detritus is a major fraction of total suspended matter in these regions.

Gordon, D.C. and P.J. Cranford (Bedford Institute of Oceanography, Dartmouth, N.S.). IMPROVED ESTIMATES OF FUNDY SALTMARSH PRODUCTION AND EXPORT.
Earlier studies in the Cumberland Basin indicated that the annual net aerial primary productivity (NAPP) of Spartina alterniflora low marshes averaged 272 gC $m^{-2}y^{-1}$ or 29% of the total annual production. More careful measurements on a similar marsh at Grand Pre in the Minas Basin suggests this estimate is at least 14% too low. Export curves at both locations show two peaks; one in the spring just after ice melt and one in the fall when new vegetation dies. Both sets of data are used to prepare monthly estimates of saltmarsh export required for the Cumberland Basin ecosystem model. The major uncertainty is the breakdown of monthly export into labile, intermediate and refractory components.

Keizer, P.D. and D.C. Gordon (Bedford Institute of Oceanography, Dartmouth, N.S.). DEVELOPMENT AND APPLICATION OF AN ECOSYSTEM MODEL FOR CUMBERLAND BASIN.
An ecosystem model of Cumberland Basin has been developed by means of a number of local and international workshops and with the aid of user-friendly modelling packages. Scientists involved in the project have learned a great deal about the functioning of this ecosystem by taking part in these workshops. The modelling process has identified many areas where our understanding of this ecosystem is incomplete and where more data or research into ecological processes are necessary. Validation of the model and sensitivity analyses must still be completed. As an example of how the model can be used, the hypothesis that detritus derived from salt marshes has a major impact on the Cumberland Basin ecosystem is examined.

DuBois-Laviolette, A. (Acadia Univ., Wolfville, N.S.). THE FORAGING AND ENERGETICS OF BLACK-BELLIED PLOVERS ON STARRS POINT MUDFLAT.

The foraging and energetics of migrant Black-bellied Plovers (Pluvialis squatarola) were studied on the Starrs Point mudflat. The major prey was the polychaete Glycera dibranchiata. Foraging behaviour of plovers is best described as a run-stop-peck activity. Birds located prey items visually and the foraging distribution of birds was not directly related to the distribution of the prey. An average capture rate of 0.28 ± 0.32 worms/min was calculated representing only a 16% success rate. However this led to a daily energy intake of 4 to 6.8 x BMR and an average rate of fat deposition of 5.1 g fat/day. To deposit fat stores necessary for migration it was estimated that plovers remained in this area for about 13 days.

White, L. (Dept. of Zoology, Univ. of Guelph, Guelph, Ont.). FAT DEPOSITION OF SEMIPALMATED SANDPIPERS DURING AUTUMN MIGRATION IN THE LOWER BAY OF FUNDY.

The seasonal weight patterns of semipalmated sandpipers reflect the respective arrival schedules of adults and juveniles at a migratory stopover. In 1983, most adults arrived between 16 July - 11 August with peaks in arrivals occurring during spring tides. Early in the migratory season, most adults weighed <30 g, while later in the season most adults weighed >30 g. Juveniles arrived in discrete waves which only coincided with spring tides. Weight changes in the juvenile population were much more rapid than those of adults, reflecting the temporally restricted arrival schedule of juveniles. Weight was found to be a good predictor of length of stay in adults. Adults weighing <30 g stayed 19-20 days, those weighing 30-39.9 g stayed 6-11 days and adults weighing >40 g stayed 1-2 days. An apparent seasonal decline in length of stay is shown to be primarily the result of changes in the weight composition of the population, from predominantly light to heavier individuals as the season progressed. Juveniles did not exhibit a relationship between weight and length of stay. The rate of weight gain of adults and juveniles was estimated to be approximately 1.08-1.26 g/day.

DeWolfe, D.L. (Discovery Consultants, Wolfville, N.S.) and Graham R. Daborn (Acadia Univ., Wolfville, N.S.). CORRELATIONS OF LONG TERM CYCLES IN FISHERIES CATCH DATA WITH THE 18.6 YEAR NODAL CYCLE OF THE TIDES IN THE BAY OF FUNDY-GULF OF MAINE SYSTEM.

Examination of some multi-year (>70 year) data sets for fish catches in the Bay of Fundy-Gulf of Maine System indicates that several important fish stocks vary in association with the 18.6 year nodal cycle of the tides. Landings of cod, halibut and haddock exhibit increases 5-6 years after years of highest tidal range, corresponding with the period from hatching to recruitment. Warm-water fish, such as menhaden, tend to show decreases 2-3 years after the highest tides. Catch-per-unit-effort data sets are too short for correlation with the nodal cycle. We suggest that the correlations indicate that either lower sea surface temperatures or higher primary productivity produced by enhanced vertical mixing during peak years of the

nodal cycle favour larval fish survival of some pelagic species. The 2.5-3.5% variation in tidal range over the nodal cycle is comparable with the predicted increase from the proposed Cumberland Basin tidal power development.

Rulifson, R.A. (East Carolina University, Greenville, NC 27834) and M.J. Dadswell (Fisheries and Oceans, St. Andrews, N.B.). TAGGING STUDIES OF STRIPED BASS (Morone saxatilis) AND RIVER HERRING (Alosa pseudoharengus and A. aestivalis) IN MINAS BASIN, NOVA SCOTIA.
The 1985 field season was the first full-scale attempt to determine the migration patterns of striped bass, alewife, and blueback herring in upper Bay of Fundy waters. River herring (gaspereau) first appeared in commercial weirs in June; peak abundance of market-sized adults occurred in July. Most river herring present in August and September were juveniles <130 mm TL. Striped bass abundance was low throughout the summer, and increased dramatically in September. Most striped bass caught in weirs were of the 300-400 mm FL size class. Hypotheses concerning local migration patterns will be presented.

Hogans, W.E., G.D. Melvin and M.J. Dadswell (Fisheries and Oceans, St. Andrews, N.B.). MORTALITY OF ADULT AMERICAN SHAD (Alosa sapidissima) PASSED THROUGH A STRAFLO TURBINE IN THE LOW-HEAD TIDAL POWER GENERATING STATION AT ANNAPOLIS ROYAL, N.S.
During spring 1985, 24 adult pre- and post-spawning American shad were introduced into the upstream end of the draft tube of the Straflo turbine at the low-head tidal power plant on the Annapolis River, Nova Scotia. Nineteen test shad were passed through the turbine successfully. Of these 9 survived turbine passage. Ten test fish introduced into the turbine showed no movement for at least 5 hours and followed patterns exhibited by three sacrificed shad put through the turbine. Thirty-nine control fish tagged with dummy tags were retained alive in holding pens for estimations of mortality due to capture, handling and tagging methods. Mean percent turbine mortality was 46.3% $\pm$ 34.7%. Observations by SCUBA divers of the river bottom off the turbine discharge opening in early July revealed large numbers of macerated fishes of several species including shad, striped bass, alewife, herring, eels and mackerel.

POSTERS

Keizer, P.D., D.C. Gordon, P. Schwinghamer (Bedford Institute of Oceanography, Dartmouth, N.S.) and G.R. Daborn (Acadia Univ., Wolfville, N.S.). CUMBERLAND BASIN ECOSYSTEM MODEL.

Daniel, S.M. (Dept. of Biology, Acadia Univ., Wolfville, N.S.). SELECTIVE FORAGING OF A NESTING COLONY OF ARCTIC TERN (Sterna paradisaea) AT AN UPWELLING AREA OF MACHIAS SEAL ISLAND, NEW BRUNSWICK, CANADA.

Helleur, R. (Dept. of Chemistry, Acadia Univ., Wolfville, N.S.). CHEMICAL ANALYSIS OF PARTICULATE ORGANIC MATTER FROM SALTMARSH GRASS: PYROLYSIS-GAS CHROMATOGRAPHIC APPROACH.

Stone, H.H. (Dept. of Biology, Acadia Univ. Wolfville, N.S.). COMPOSITION, MORPHOMETRIC CHARACTERISTICS AND FEEDING ECOLOGY OF ALEWIVES (Alosa pseudoharengus) AND BLUEBACK HERRING (A. aestivalis)(Pisces: Clupeidae) IN MINAS BASIN.

MacFarlane, R. (Dept. of Biology, Acadia Univ., Wolfville, N.S.). FOULING COMMUNITIES ASSOCIATED WITH THE ANNAPOLIS RIVER ESTUARY.