Science Review 1988 & '89

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Research

1988 and '89 in review

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D. I. Ross. S. B. MacPhee, and H. B. Nicholls

The years 1988 and '89 were interesting and fruitful ones for the research and survey programs carried out at the Bedford Institute of Oceanography, the Halifax Fisheries Research Laboratory, and the St. Andrews Biological Station. In the following paragraphs, information is provided on a number of the significant events that occurred during those years at the laboratories of the Department of Fisheries and Oceans (DFO) and at those of the Department of Energy, Mines and Resources (DEMR), and Environment Canada.

Staff

Key staff changes that occurred at DFO during the review period are as follows. In February 1988, Dr. Michael Sinclair was appointed Director of the Biological Sciences Branch (BSB), replacing Dr. James Stewart, who returned to his position as Research Scientist. Also within BSB, Dr. Donald Gordon was appointed Head of the newly formed Habitat Ecology Division. Dr. John Pringle was appointed Head of the Fisheries and Benthic Aquaculture Division and Director of the Halifax Fisheries Research Laboratory. Dr. John Ritter became Head of the Freshwater and Anadromous Division on the retirement of Mr. Neil MacEachern. There were no senior staff changes in the Physical and Chemical Sciences Branch. In the Hydrography Branch, Mr. Paul Bellemare was appointed Regional Director of Hydrography in May 1988. Subsequently, Mr. Reginald Lewis was appointed Regional Field Superintendent.

The following senior staff changes were made in the Atlantic Geoscience Centre (AGC) of DEMR. In August 1988, Dr. David Ross was appointed Director of AGC, succeeding Dr. Michael Keen, who returned to his position as Research Scientist. Dr. David Prior was appointed Head of the Environmental Marine Geology Subdivision, and Dr. Matthew Salisbury was appointed Head of the Regional Reconnaissance Subdivision.

There were no senior staff changes within the laboratories of Environment Canada.

Awards, appointments, and presentations

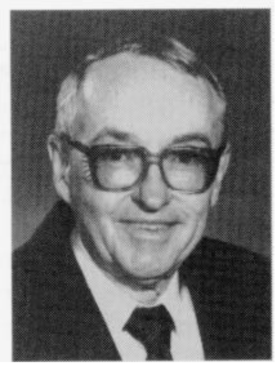
The following were among the awards, appointments, and presentations involving staff of the laboratories:

- Dr. Allyn Clarke (DFO) was appointed Co-chairman of the Scientific Steering Group of the World Ocean Circulation Experiment (WOCE);
- Dr. John Castell (DFO) assumed the Presidency of the World Aquaculture Society, replacing Dr. David Aiken;
- Dr. Trevor Platt (DFO) was the 1988 recipient of the G. Evelyn Hutchinson Medal of the American Society of Limnology and Oceanography, the highest award given by the society;
- Kate Moran (DEMR) was appointed Chairperson of the Shipboard Measurements Panel of the international Ocean Drilling Project; and
- Dr. A.R. Longhurst (DFO) was elected a Fellow of the Royal Society of Canada.

Huntsman Award: The A. G. Huntsman Award for excellence in the marine sciences is awarded annually. It is administered by a private foundation based at BIO.

The following two Huntsman Awards were presented during the period covered by this *Review.*

Dr. Carl Wunsch



Dr. Lawrence R. Pomeroy

On November 2, 1988, Dr. Carl Wunsch of MIT was presented with the A. G. Huntsman Award for 1988 in recognition of his major contributions to the development of innovative analytical techniques applicable to the interpretation of oceanographic data sets and for his scientific leadership in preparing plans for global climate research programs in the 1990s.

The A. G. Huntsman Award winner for 1989 was Dr. Lawrence R. Pomeroy of the University of Georgia. Dr. Pomeroy was recognized for his fundamental research demonstrating the importance of bacterial food chains in the oceans. He was awarded the prestigious medal on November 22, 1989.

Research and survey highlights

Some of the major events occurring during the review period are listed below by broad geographic region.

Georges Bank, Bay of Fundy, Scotian Shelf Deep crustal seismic studies carried out under the Geological Survey of Canada's Frontier Geoscience Program (FGP) have provided new evidence on the formation of east coast continental margins and the associated marginal basins. During the review period, emphasis shifted from the margins of the Grand Banks to the Scotian Shelf in order to provide information on the deep structure of the Scotian Basin and to provide structural control from the Meguma rocks of Nova Scotia to the ocean basement east of the Nova Scotia margin. These studies have been complemented by collaborative studies with scientists from Germany conducted under the Canada/Germany bilateral agreement.

Major research studies involving physical, chemical, and biological sciences were carried out on Georges Bank in 1988 and 1989. The studies included research on circulation and mixing associated with the tidal front, as well as turbulence measurements and studies on plankton production and larval distribution in the frontal area.

Substantial progress was made in phytotoxin research, with projects introduced in such diverse fields as biochemistry, phytoplankton ecology, and physiology, as well as microbiological and aquatic toxicology. As part of this program, phytoplankton profiling was initiated in the spring of 1989 in order to determine phytoplankton composition of selected inlets on a regular basis. The purpose of this program is to provide information about the areas and times that are unfavourable for mariculture due to the presence of toxin-producing species.

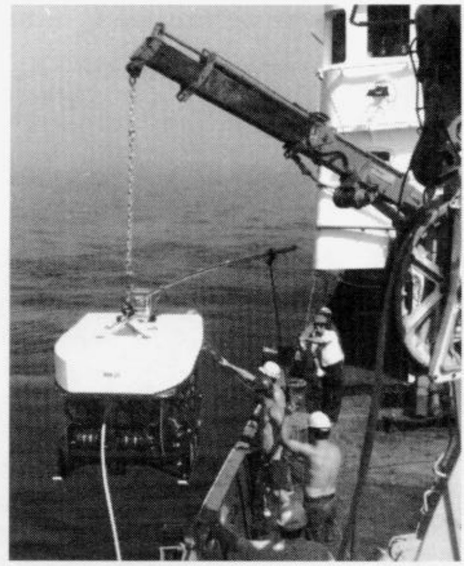
The review period was an active one for aquaculture research and development. Responsibility for DFO's Salmon Demonstration and Development Farm was transferred to the New Brunswick Salmon Growers Association, and active research programs were pursued in the areas of nutrition, disease, disease control, and genetics. The principal species for aquaculture research are Atlantic salmon, halibut, striped bass, lobster, and blue mussels. DFO's five hatchery facilities operated at peak capacity, delivering over one million smolts each year to river enhancement programs and private aquaculture farms.

A research program on silver hake was initiated to aid in the management of this resource and to study the role of the species in the Scotian Shelf ecosystem.

Studies of the morphology and chemical contamination of the sediments in Halifax Harbour have provided significant input to the assessment of the design and location of appropriate sewage treatment facilities for the Halifax-Dartmouth metropolitan area. Ongoing research in this field will lead to improved understanding of the remobilization and dissemination of contaminants within the sediments of estuary systems. Other research in Halifax Harbour has included benthic biological investigations, physical oceanographic investigations, studies of dissolved and particulate trace metal distributions, and the examination of contaminants in lobsters. (On this topic, see the essay in this *Review* titled "Halifax Harbour: How the currents affect sediment distribution".)

A major interdisciplinary project introduced during the review period is employing ecological modelling techniques to examine the environmental impact of salmonid aquaculture in L'Etang Estuary in southwestern New Brunswick. The study is designed to provide information about the number of salmon cages the estuary can support without having serious environmental effects.

In June 1989, the second set of east coast trials on the remotely operated Hysub 5000 undersea vehicle (ROV) was carried out from C.S.S. Dawson. In 1988, trials had been conducted off Bermuda using a vessel from the Department of National Defence. Twelve principal investigators carried out experiments which included examining flow patterns from sewer outfalls to determine the effect on the seafloor, photographing zooplankton and euphausiid layers in Emerald Basin, mapping dredge spoils, and examining and photographing scallop and lobster habitats.



The ROV being deployed from the C.S.S. Dawson.

The review period was also active in terms of grey seal research. Seal population trends were studied by tagging all pups born on Sable Island. In addition, and in cooperation with Guelph and Dalhousie Universities and with Fisheries Resource Development Ltd., a research program was undertaken to investigate the deworming of seal populations, the immunological relationships between seals and the sealworm, and the use of birth control agents and other techniques to reduce and limit grey seal populations.

Considerable steps were taken during 1988 and '89 to improve interaction and the sharing of knowledge between scientists and fishermen. This process included seminars, opportunities for fishermen to join research surveys and for scientists to join fishing vessels, and the dispatch of printed material to fishermen on a regular basis.

Grand Banks, Labrador Sea: Scientists from AGC and Brock University collaborated on a geophysical interpretation of the magnetic anomaly of the Labrador Sea and Orphan Basin. The purpose of the study was to understand the nature of the region's underlying rock in order to decipher the history of the rifting that created the continental margin and subsequently affected the development of the sedimentary basins that now populate the continental shelf.

The completion of the first five years of

A seal pup being tagged on Sable Island.

the Frontier Geoscience Program of the Geological Survey of Canada saw the publication of the Labrador Sea basin atlas. This is the first of several east coast basin atlases synthesizing the history of the formation and development of the offshore basins.

During the review period, a new hydrocarbon appraisal of the Jeanne d'Arc Basin on the northeast Grand Banks was completed by DEMR's Petroleum Resource Assessment Secretariat. AGC staff participated by providing the geological input to the analysis and assessment components of the assessment.

C.S.S. *Baffin* returned to BIO on October 6, 1989, having completed an extensive multiyear hydrographic survey of the Labrador Coast. In particular, hydrographers from *Baffin* surveyed the approaches to Nain, which marked the completion of a route survey from Hamilton Inlet to Nain. A total of ten charts cover this area, seven of which have been published, with the remaining three to follow.

Arctic: In early 1989, scientists operating from *C.S.S. Baffin* carried out a broad survey of temperature, salinity, and chemical tracers in the Greenland Sea Gyre. The purpose of this experiment, repeated several times over the period from February 1988 to September 1989, was to determine how much surface water is cooled during the winter and sinks to form the deep waters of the ocean. The first measurements of carbon tetrachloride levels in the Greenland Sea were obtained during the cruise. This additional chemical tracer should allow a more precise estimation of the renewal rates of the Greenland Sea.

Staff continued research from the Canadian Ice Island as it moved along the northern Canadian margin. (On this topic, see the essay in this *Review* titled "Canadian Ice Island: Environmental studies of the polar margin north of Canada's arctic islands".)

In August 1989, *C.S.S. Dawson* recovered an array of five current meter moorings from Davis Strait, and deployed replacements. This represented the second successful recovery of year-long moorings at this location. The moorings are designed to measure water transport out of Baffin Bay into the Labrador Sea.

Offshore: The Hydrography Branch of DFO's Scotia-Fundy Region was involved in a number of significant events in the field of electronic charting. One of these was the North Sea Electronic Chart evaluation trials, during which the Canadian Hydrographic Service Electronic Chart Testbed was demonstrated onboard 'the Norwegian vessel *Lance.*

During the period from April to May 1989, DFO scientists contributed to the international Joint Global Ocean Flux Study pilot experiment in the western North Atlantic. DFO's studies focused on the northern progression of the spring phytoplankton bloom and ground-truthing satellite measurements of chlorophyll abundance in the Sargasso Sea and east of Flemish Cap.

The first field activity of a joint project between AGC and IFREMER (France) to study continental slope stability was successfully completed off Nice in 1989. AGC provided a Huntec DTS seismic profiling system to examine sediment instability at the site of the 1979 sediment failure, when part of the Nice airport slumped into the sea and triggered a powerful submarine turbidity current.

AGC staff continued active participation on the international Ocean Drilling Project. During the review period, Dr. Felix Gradstein was co-chief scientist on the Indian Ocean leg 123, part of an integrated scientific venture to drill a transect of holes from the Exmouth Plateau west of Australia to the Argo Abyssal Plain in the Indian Ocean. The successful expedition showed that the Indian Ocean was significantly younger than was previously thought. As a result, the history of the Indian Ocean's spreading is being reviewed internationally.

Non-site-specific: Studies pertaining to the operations of commercial fisheries included consideration of the implications of an increase in minimum trawl mesh size. In addition to mesh size, the possible benefits of adopting square mesh netting as opposed to traditional diamond mesh netting were also studied.

The role of zooplankton in exporting nitrogen out of the surface layers of the ocean during their die1 migration was the subject of an important research study. The hypothesis under investigation is whether the phytoplankton consumed at night by zooplankton in the surface layers, and excreted during the day in deeper layers, account for a significant transfer of nitrogen out of the surface layer.

The Littoral Investigation of Sediment Properties (LISP) program was carried out in 1989 and involved scientists from many disciplines working together to study the interrelationship among the physical, geological, biological, and chemical properties of sediment in an intertidal estuary. The study emphasizes the processes by which fine-grained sediments form by simultaneously measuring attributes of the sediment and of the environment in which they occur, and by examining the relationship of atmospheric factors to the stability of the exposed tidal flat.

Finally, environmental marine geologists from AGC implemented two new programs of enhanced coastal studies under the Geological Survey's New Initiatives program. The Marine Geoscience (Coastal Nearshore) Initiative will provide an integrated national approach to research on coastal geological problems, while at the same time addressing specific issues relating to urban and commercial development. The GSC Global Change Initiative provides impetus for AGC's focus on environmental change records in marine sediments and its work on carbon flux and sea-level change.

Task force membership

Staff were appointed to a variety of task forces and other working groups during the review period, including the following:

- DFO's science sector actively participated in the Scotia-Fundy Groundfish Task Force organized under the chairmanship of J.-E. Haché, the Regional Director-General. The purpose of this task force was to prepare an action plan to deal with the problems of the Scotia-Fundy groundfish industry and to develop recommendations to lead to the long-term stability of this industry. Marine Fish Division Chief R. O'Boyle represented the science sector on the task force.
- Several staff of the BIO were appointed to the Halifax Harbour Task Force, which was established by the Province of Nova Scotia to review and make recommendations pertaining to the marine environmental implications of a proposed Halifax-Dartmouth metropolitan area sewage treatment facility. The staff involved were G. B. J. Fader, D. C. Gordon, H. B. Nicholls, and B. D. Petrie.
- D. Prior of AGC was appointed Chief Technical Advisor on marine engineering geology to the Pearl River Mud Basin, South China Sea, United Nations Development Project.
- S. B. MacPhee and S. Kerr of DFO participated in the task force on the Ocean Production Enhancement Network (OPEN), one of the federal Centres of Excellence.
- H. B. Nicholls represented DFO as one of several Canadian and U.S. federal observers on the Gulf of Maine Working Group. Membership on the working group comprises New Brunswick, Nova Scotia, Maine, New Hampshire, and Massachusetts.

Conferences and workshops

During the review period, the following conferences and workshops were among several sponsored (in whole or in part) and held at DFO's three regional facilities:

- Acoustics Workshop - The first national hydroacoustics workshop was held at BIO from March 1 to 3, 1988. The workshop included presentations on the applications of acoustic technologies in fisheries research, biological and physical oceanography, hydrography, the geosciences, and marine mammal research.
- Sealworm Workshop - An International Sealworm Workshop was held at the Halifax Fisheries Research Laboratory from June 20 to 24, 1988. The workshop was attended by 29 scientists from Norway, Iceland, West Germany, the United Kingdom, and Canada. This was the continuation of an event, the first part of which had been held in the previous year.
- Interdisciplinary Conference on Natural Resource Modelling and Analysis (ICNRMA) - This international conference, co-hosted by DFO and St. Mary's University, featured scientists from over a dozen countries. It was held at BIO from September 29 to October 1, 1988.
- Long-Range Transport of Atmospheric Pollutants (LRTAP) Workshop - The third annual federal LRTAP workshop was held at BIO from November 15 to 17, 1988. Among the topics discussed were the use of liming to prevent the adverse effects of acidification and an assessment of the significance of airborne organic and metal pollutants.
- Aquaculture Workshop - A Canada/Norway aquaculture workshop was held at the St. Andrews Biological Station in September 1989. The workshop encompassed all aspects of finfish aquaculture, including disease/nutrition, environmental effects, genetics, physiology, and growout techniques, with a strong emphasis on Atlantic salmon.
- Canadian Continental Shelf Seabed Symposium - This international conference was held at BIO from October 2 to 7, 1989. Its purpose was to exchange knowledge, develop new research thrusts, and document current research on the nature and stability of the Canadian continental shelf seabed in terms of the physical and chemical environments and the associated biological communities.
- Georges Bank Workshops - International workshops were held at BIO on November 8 and 9, 1988, and November 7 and 8, 1989. Papers were presented on a wide range of topics, including physical and biological oceanography, marine ecology, fisheries, and the potential impacts of hydrocarbon development.
- Halifax Inlet Research Workshop - The purpose of this workshop, held at BIO on November 9, 1989, was to provide an informal forum for the presentation and discussion of research results and plans pertaining to Halifax inlet. Because of the proposed installation of a major sewage treatment facility, Halifax inlet has been an area of considerable scientific investigation during the review period. One hundred persons from a variety of agencies and interest groups attended the workshop.

Technology transfer

On May 26, 1988, an exhibition was held at BIO featuring cooperative programs between Canadian ocean-industry companies and scientists from DFO/DEMR. The event involved over 50 exhibitors from industry, universities, and government. Among the many items on display were several resulting from technology transfer involving DFO and DEMR scientists at BIO, the St. Andrews Biological Station, and the Halifax Fisheries Research Laboratory. Other technology transfer highlights during the review period include the following:

- A license was obtained by Seastar Instruments Ltd. of Dartmouth to build and market AGC's ocean-bottom seismometer.
- A licensing agreement was signed with

Brooke Ocean Technology Ltd. to produce and market a sheave block developed at BIO.

- Seimac Ltd. of Dartmouth was awarded a contract in the fall of 1989 to develop a Biological Up Down (BUD) probe. The instrument will relate the small-scale physical environment, the available light, and the biological production in the upper ocean. It will be an extension of the EPISONDE concept developed by BIO.
- "Pacem in Maribus XVI", a conference and exhibition covering ocean technology development, training, and transfer, was held in Halifax from August 23 to 24, 1988. DFO staff were involved in the coordination of the event, which was sponsored by the International Ocean Institute (of Malta, Sweden, and Halifax, Canada).
- Funding was arranged for contracts with several private sector companies to develop a new at-sea handling technology for the remotely controlled vehicle DOLPHIN.

Visitors

As in previous years, the three regional establishments received many special visitors from Canada and abroad. Of particular interest were the visits to BIO by the following: the Senate of Canada Standing Committee on Fisheries; Dr. Byong-Kwon Park, Director of the Korean Ocean Research and Development Institute; the Brander-Smith Public Review Panel on Tanker Safety; and Dr. John Woods, Director of Marine Sciences, Natural Environment Research Council, U.K.

Support services

With regard to support services, the following are among items of interest:

- Upon the completion of a mid-life refit, C.S.S. *Hudson* returned to BIO on October 21, 1989, after an absence of over one year. The improvements made will enable the vessel to provide continued useful service to the scientific community on the Atlantic coast for many years to come.
- On December 1, 1989, the vessel *Frederick G. Creed* arrived at BIO for a three-month period to assess her capability for hydrographic surveys, scientific research, and fisheries patrol. The *Creed* is a 20-metre SWATH (small waterplane area twin hull) vessel. Vessels of this nature have considerable potential for increasing the operational window, especially in circumstances where inclement weather conditions often hamper at-sea operations.

Publications

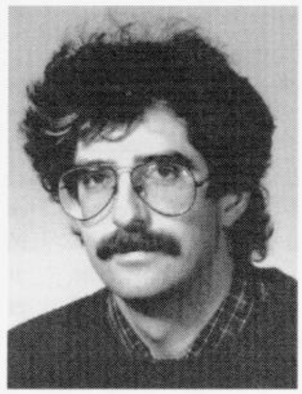
The output of the establishments reaches their respective clients and customers through a variety of means, including scientific articles, reports, and nautical charts. During 1988 and '89, the published output of the establishments continued at a high level. In particular, several books and atlases were produced. Full details are provided in the section of this *Review* entitled "Charts and Publications".

The SWATH vessel Frederick G. Creed.

Fluid-rock interactions in sedimentary basins: A new research direction for the Atlantic Geoscience Centre

M. E. Best and B. S. Mudford

M. E. Best



B. S. Mudford

Sedimentary basins make up a large and important component of Canada's land mass, both onshore and offshore. They contain much of our natural resources, including all of our oil and gas. This has led to many detailed investigations, ranging from surveying and mapping of the geology of the basins, to more theoretical work aimed at understanding how sedimentary basins develop. Work of this nature is carried out by many researchers at the Atlantic Geoscience Centre (AGC), in collaboration with colleagues in industry, academia, and other government laboratories. Although much effort has been expended in studying sedimentary basins, we still lack detailed understanding of many of the processes which occur in them. This is especially true of those processes which occur over the long time scales (of the order of millions of years) characteristic of sedimentary basin development. In this article, we describe a new research direction that AGC is taking in order to understand fluid-rock interactions within the sedimentary basins.

Sedimentary basin processes

A sedimentary basin is a complex agglomeration of solid and fluid components. Clastic sediments (sandstones and shales) are initially deposited as a mixture of relatively large amounts of water and solid material. As they are buried through time, the sediments are compacted and much of this water is expelled. Carbonate (limestone and dolomite) development in sedimentary basins is controlled by water temperature and depth and the clastic input. Fluctuating sea level and elastic input produce interlayered beds of elastic and carbonate sediments. During burial, the temperature increases, allowing several chemical reactions to become possible. These reactions alter the character of the original sediments, changing them to rock, and they alter the chemical composition of the pore water, as well as generating or reducing the pore fluids. They are generally termed diagenetic reactions.

These chemical reactions occur against a background of hydrodynamics with large-scale, although extremely slow, flow of fluids seeking equilibrium. Fluid flow contributes to the efficiency of many of the reactions. At present, there is only a limited understanding of the interrelation of these complex processes. Their effects over the long time scales characteristic of sedimentary basin development need to be investigated.

We shall limit our discussion in this paper to fluid flow in the sediments and to diagenetic interactions. A number of the processes that occur in a sedimentary basin are depicted in figures 1 through 4. Of course, the dominant process is sediment deposition, without which a basin could not develop. Sedimentary basins are generally initiated in response to a tectonic event. For example, the Scotian Basin formed in response to the opening of the

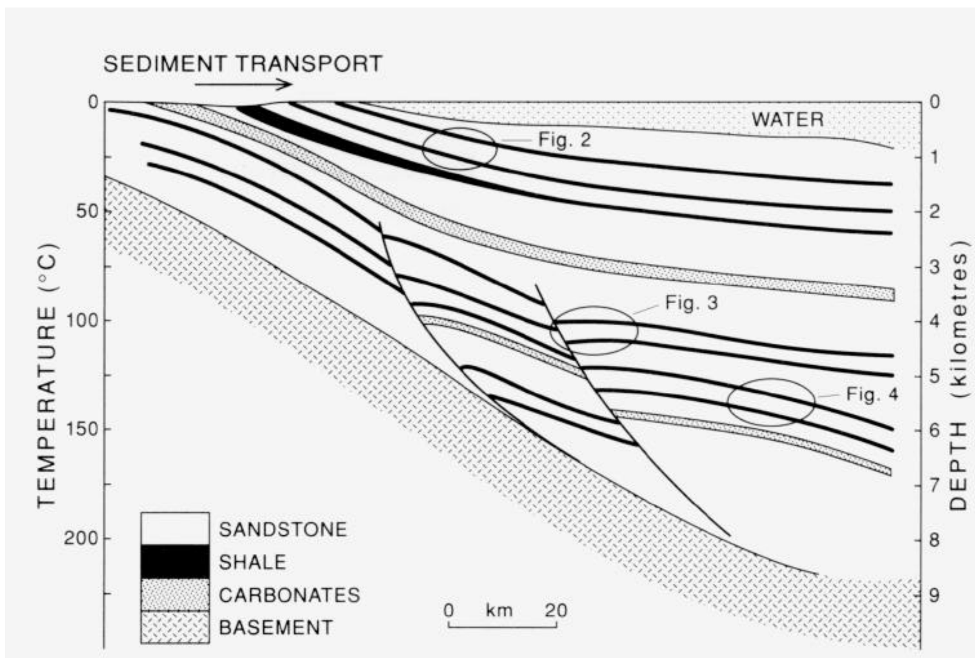


Figure 1. A geological section of a sedimentary basin, depicting zones of fluid-rock interaction as a function of depth. The three circled regions are enlarged in figures 2 through 4 to show more detail.

Atlantic Ocean. After the initial rifting event, it was the site of a major delta for the protoriver of the St. Lawrence system. Sediments continued to be deposited as a result of changing sea levels and subsidence of the basin due to the cooling and contraction of the crust after the relatively high temperatures induced during the rifting.

As sediments accumulate, the weight of the overlying sediments causes compaction and some of the water initially contained in the pores is squeezed out. At shallow depths (Fig. 2), the sediments have high porosity (the amount of pore space in the sediments) and are relatively permeable (the measure of fluid flow through them). Coarser-grained sediments - for example, sandstones - will allow fluid to pass through more easily than will finer-grained sediments - such as mudstones and shales. Carbonates are more complex, and their permeability and porosity are difficult to predict. In any case, at shallow depths fluids can move relatively easily in both vertical and horizontal directions. For this reason, fluid pressures are generally hydrostatic in the shallow part of sedimentary basins, since the fluid is in communication with the sediment surface.

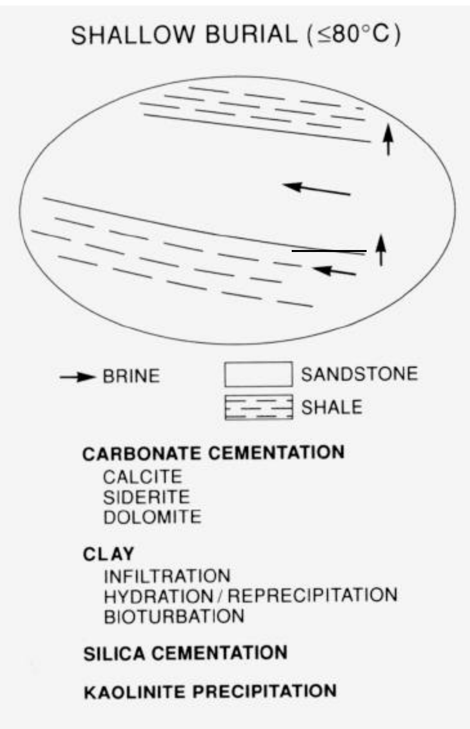


Figure 2. Shallow burial and low-temperature zone (<80°C). The chemical reactions that can occur in this zone are listed. The arrows represent the direction and relative magnitude of waterflow in the system.

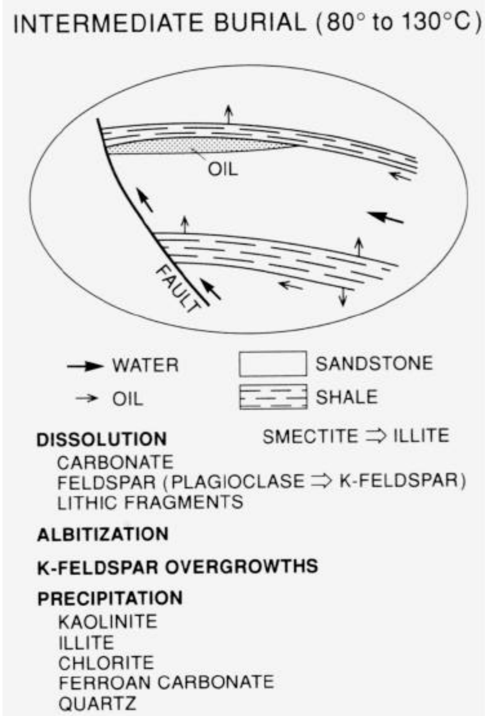


Figure 3. Intermediate burial and temperature zone (80°C to 130°C). The chemical reactions that can occur in this zone are listed. The arrows represent the direction and relative magnitude of water and oil flow in the system.

With increasing depth of burial, the sediments become more compacted and the porosity and permeability decrease. If fine-grained sediments are present, then the permeability may decrease enough to significantly impede fluid flow, thus creating a barrier or seal. As burial continues, this barrier can prevent the dewatering of underlying sediments, leading to the generation of fluid pressures above hydrostatic pressure (that is, overpressures).

Many fine-grained clastic sediments (shales) and some carbonates contain organic debris. As the temperature increases during burial, some of this organic material is chemically transformed into hydrocarbons, either oil or gas. This class of diagenetic reactions creates additional fluids (and, therefore, fluid volume) in the basin. If there are sufficient amounts of the correct type of organic material (that is, predominantly marine-derived), oil will be produced at temperatures within a given range. At higher temperatures, oil will be cracked to form gas. Finally, a temperature will be reached above which no more hydrocarbons are produced. Oil is therefore generated at shallower depths (Fig. 3) than gas (Fig. 4). The depths at which oil and gas are generated depend on the type of organic materials and the vertical temperature gradients. There are other types of organic debris (predominantly terrestrially derived) that generate only gas.

As hydrocarbon generation continues in the low-permeability "source rocks", the concentration increases until hydrocarbons are expelled (primary expulsion) into the more permeable (usually by several orders of magnitude) surrounding sandstones and carbonates. The permeable sediments allow the hydrocarbons to migrate by buoyancy-driven flow (Figs. 3 and 4), since hydrocarbons are less dense than water. They continue to flow either until they reach an impermeable seal (trap) and accumulate to form a reservoir, or until they escape from the basin. Hydrocarbon reservoirs are not permanent traps over geological time scales and are, therefore, transient events.

For example, figure 3 depicts a fault acting as a lateral barrier to fluid flow. In this case, overlying shale acts as a seal to

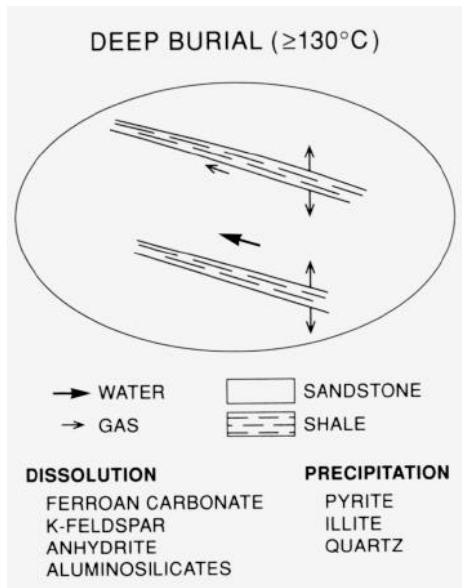


Figure 4. Deep burial and high-temperature zone (>130°C). The chemical reactions that can occur in this zone are listed. The arrows represent the direction and relative magnitude of water and gas flow in the system.

the fluids in the anticlinal structure, thus forming a good trap for hydrocarbons. Fluid flow in the vicinity of the fault barrier will predominantly be along the direction of the fault, as shown in figure 3. If hydrocarbons migrate into a closed structure, they may increase the fluid pressure above the hydrostatic pressure and lead to overpressuring.

In a laterally confined sedimentary section, hydrodynamic equilibrium in the more permeable rocks is achieved relatively rapidly. As the sedimentary section is buried, the presence of impermeable shales and, perhaps, carbonates can give rise to vertical pressure profiles that are out of hydrodynamic equilibrium. This is due to slow vertical-flow velocities through these rocks, on the order of 1 to 10 metres per million years. The slow flow rates are the reason overpressured zones exist at all. Hydrodynamic equilibrium over geological time scales is eventually reached, even at these slow rates; hence the reason for our earlier statement that such phenomena are transient.

Most diagenetic reactions in sedimentary basins produce mineralogical and pore-fluid changes that alter sediment porosity and permeability. Such reactions, which depend on depth (or temperature), can have a pronounced effect on fluid flow paths in the basin. Figures 2 through 4 list the typical reactions that occur in a basin. The temperature determines probable reactions, but they can not occur unless the mineralogy and pore-fluid chemistry are suitable.

Diagenetic reactions of elastic sediments that occur in shallow, low-temperature sediments (Fig. 2) generally produce a variety of intergranular cements, the most prevalent one being carbonate cement. The cements have a significant effect on subsequent diagenetic processes during intermediate burial. In particular, they retard mechanical compaction by giving the rock framework additional strength, and their distribution affects the passage of fluids through the system. Kaolinite and silica precipitation affect later diagenesis and the fluid-flow characteristics of elastic sediments. Clay and oxide rims form another set of diagenetic reactions that occur during early burial. They often lead to the formation of chlorite rims during later diagenesis that reduce quartz cementation during intermediate burial.

The intermediate burial zone (Fig. 3) turns out to be a zone of intense diagenesis. It is the temperature region where most porosity-enhancing reactions occur. For example, carbonate cements which precipitated earlier and aluminosilicate framework grains (for example, feldspars) are often dissolved in this zone. Unfortunately, it is also the temperature range (80°C to 130°C) where reactions leading to the precipitation of kaolinite, illite, chlorite, quartz, and other minerals occur. The relative importance of the competing processes of dissolution and cementation depends on the composition of the water and the mineral content of the sediments.

At depths where the temperature is above 130°C (Fig. 4), the dissolution of potassium feldspar, anhydrite, and aluminosilicates forms another class of diagenetic reactions. The main porosity-reducing reaction is quartz cementation. Porosity reduction by quartz cementation can be inhibited by the development of chlorite rims in the pores (as discussed earlier), by early hydrocarbon migration, and by overpressuring. The thermal reduction of sulphate by hydrocarbons begins at approximately 140°C. This reaction is considered to account for the additional dissolution of feldspar, carbonate, and sulphate minerals, and for the formation of such products as illite, chlorite, and pyrite that occur in deeply buried clastic systems.

This is a brief overview of the very complex chemical reactions and fluid flow behaviour that occur in a sedimentary basin. In the next section we shall describe a simple model which AGC developed for investigating the effects of several of the above-mentioned processes relating to the causes of overpressuring.

Overpressure modelling

In many areas of the world, drilling operations have encountered pore-fluid pressures greater than hydrostatic pressures. Drilling in overpressured environments causes problems ranging from stuck drill pipes and lost circulation to disastrous blowouts. Understanding and predicting the characteristics of the overpressured zones in any gas or oil field is necessary if economic and safe development of the field is to be achieved.

Overpressuring occurs over a large portion of the Sable Subbasin on the Scotian. Shelf, located offshore of Nova Scotia. Because the area has important economic significance, AGC carried out a study to investigate the physical processes that cause this phenomenon. A one-dimensional (vertical) model was developed. The model is capable of investigating the

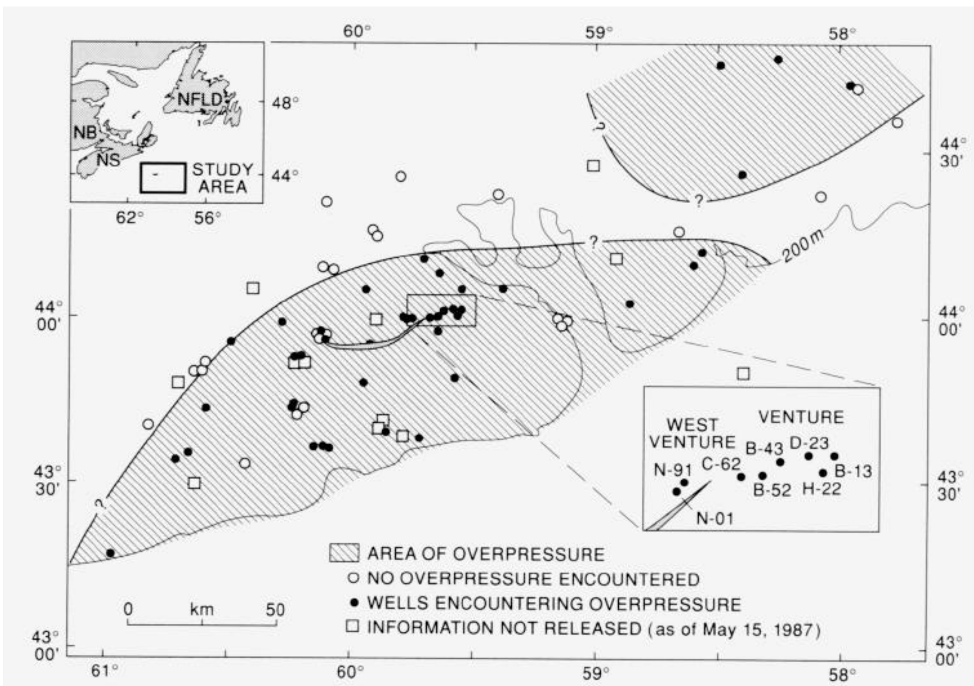


Figure 5. The Sable Subbasin on the Scotian Shelf and the region of overpressuring. The inset shows the wells in the Venture Gas Field that were used in this study.

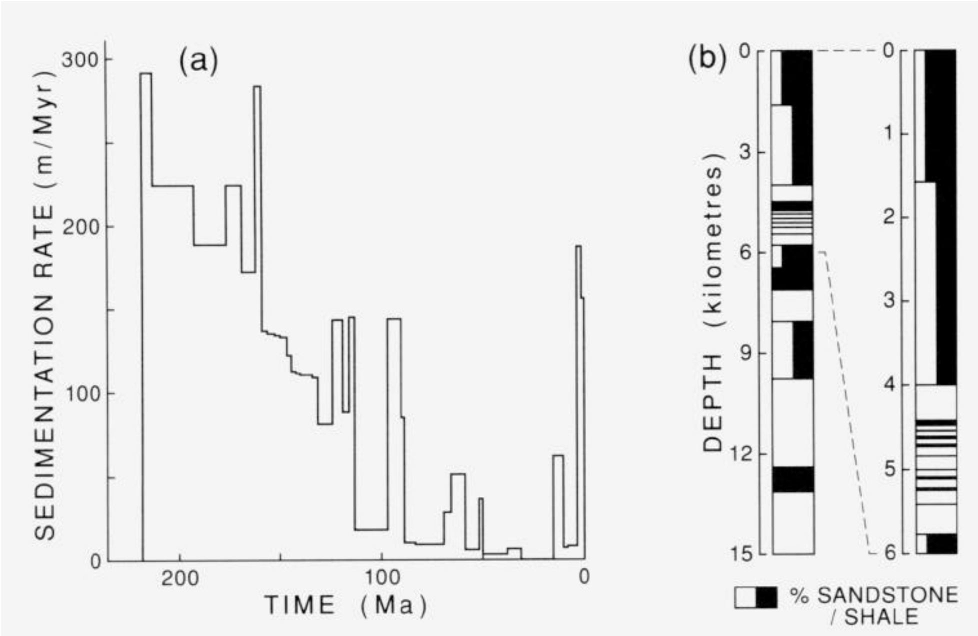


Figure 6. Compaction effects: (a) sedimentation rate versus time, and(b) sediment column. The data were obtained from the Venture Gas Field wells.

effects of compaction, thermal expansion, and hydrocarbon generation as they occurred during the development of the basin over geological time scales (millions to hundreds of millions of years). Figure 5 is a location map showing the overpressured region of the Sable Subbasin and the Venture Gas Field where our modelling has concentrated.

A typical example of compaction is depicted in figure 6. Part (a) shows sedimentation rate versus time, and part (b) shows the sediment type versus depth. Figure 7 shows the corresponding pressure profiles versus depth for three different times. The sediment column and the sedimentation rate versus time were calculated from lithologic and biostratigraphic data using wells from the Venture Gas Field. The pressure data at present day (0 Ma) were obtained from well measurements - for example, drill-stem and production tests. The different pressure responses at 90 Ma and 45 Ma in part (b) are related to the sediment rates (see part (a)). At 90 Ma, the sediment rate is high (150 m/million years), while at 45 Ma it is very low (10 m/million years). The jumps in the calculated pressure at 0 Ma are caused by the thin shale beds observed at depths between 4,500 and 5,500 m. This example shows how such a model can be used to investigate the effects of lithology and sedimentation rate on pore pressure.

Figure 8 includes the effect of hydrocarbon generation for the sediment data given in figure 6. The amount and type of organic material can be varied in the model to investigate its effect on the pressure. In this case, the amount of Type III organic material in the shale was 2%. This is terrestrially derived organic material prone to gas generation. Once a model like this has been developed, it can be used to investigate the effect of parameters and to look at their relative importance. The model can indicate deficiencies in the database where new measurements are required. It can be used to compare processes in different basins and to predict overpressuring. Other processes, such as the transformation of the clay-mineral smectite to illite with the release of bound water, can be added to this model with little additional effort once the basic numerical methods have been developed.

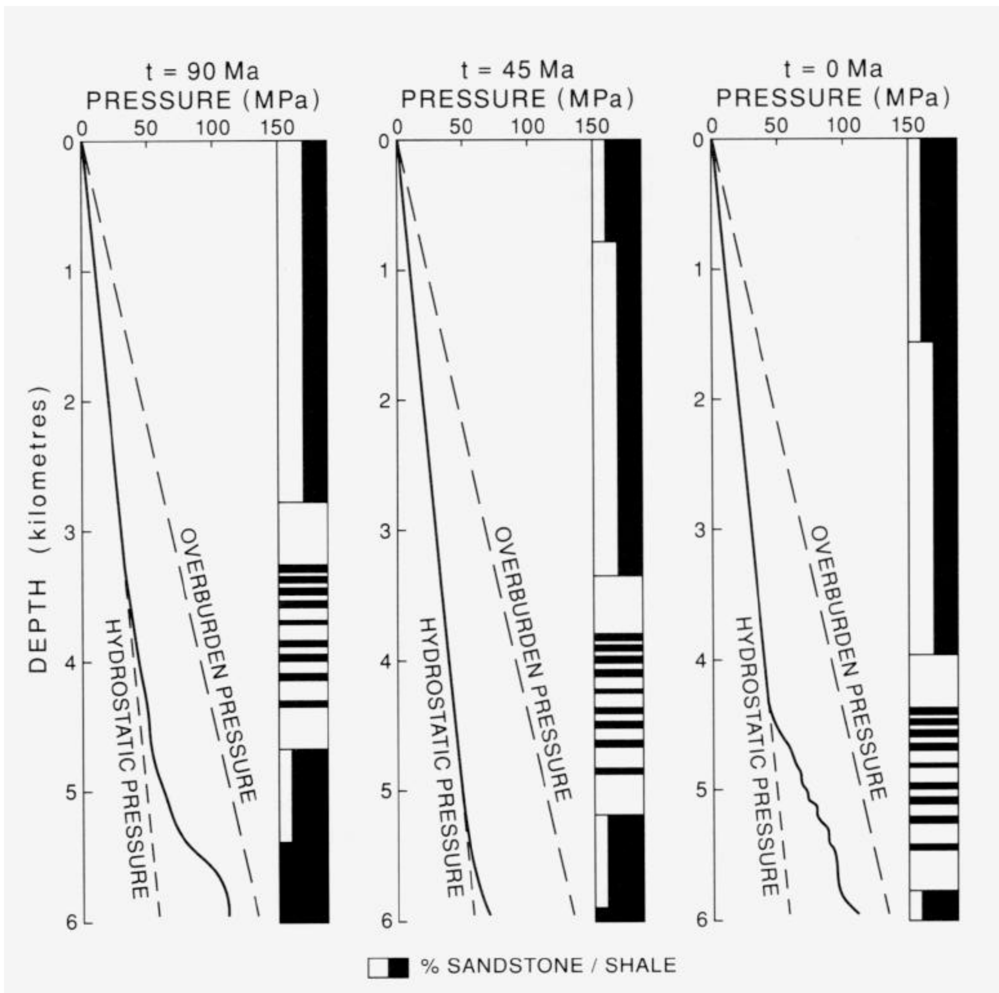


Figure 7. Pressure-versus-depth profiles at times of 90 Ma, 45 Ma, and 0 Ma, using the compaction data in figure 6.

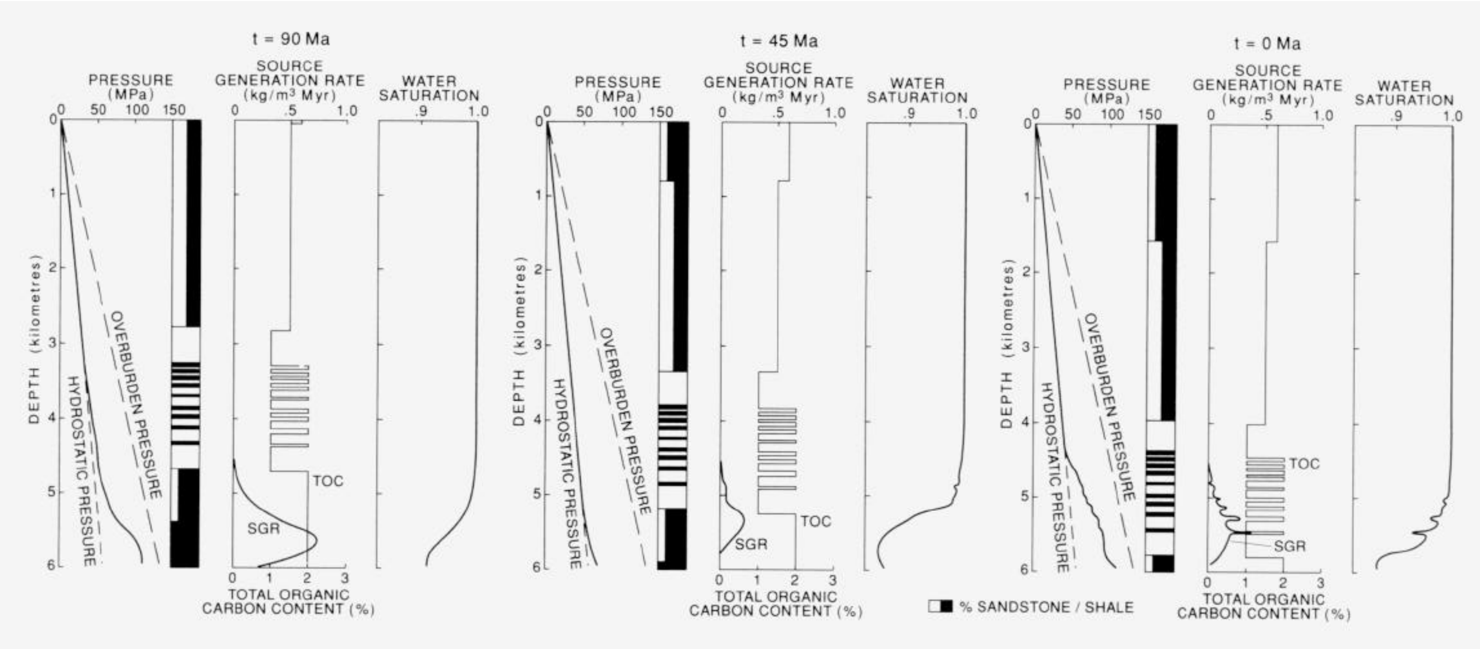


Figure 8. Pressure-versus-depth profiles at times of 90 Ma, 45 Ma, and 0 Ma. The sedimentation rate and sediment column used are the same as in figure 6. Hydrocarbon (gas) generation was included in the model by allowing 2% of the shale to consist of type III organic material (terrestrially derived organic debris).

Future research

There are a number of important questions related to basin processes that must still be answered. For example, what are the effects of diagenesis on hydrocarbon and pore-water generation, porosity and permeability distribution, fluid migration pathways, and pore-pressure distribution? How do such processes depend on the basin history? Some of these questions have been partially answered and others have never been addressed.

Numerical models that simulate basin processes provide a tool for investigating the effect of variations of the physical parameters on the development of the basin. In order to do this, two- and three-dimensional models must be constructed that incorporate fluid flow, heat flow, and diagenetic processes. They must be dynamic (time-dependent) if basin development over geological time scales is to be realistically represented. The simultaneous flow of water, oil, and gas, the generation and, where appropriate, loss of fluids, the thermodynamic and temperature-dependent reactions for organic and inorganic diagenetic processes, and many other physical parameters must be properly included in such models.

Measurement of the physical and chemical properties of specific sediments, either *in situ* or in the laboratory, is a necessary part of such studies. For example, measurement of the absolute permeability of shale and the relative permeabilities of multiphase fluid flow in shales at pressure and temperature ranges encountered in sedimentary basins is essential if pore-pressure distributions are to be properly understood and modelled. The kinetic-reaction parameters for temperature-dependent diagenetic processes are not well constrained. Measurement of these parameters would greatly aid understanding of the processes that occur during the development of a basin.

In conclusion, a balanced research program that includes numerical modelling, the measurement of physical properties, and basic parameterization of the physical and chemical processes is necessary in order to advance our understanding of basin development and the relevant processes. The Atlantic Geoscience Centre is embarking on exactly such a long-term research program to expand the necessary knowledge base for future oil and gas exploration and development on the east coast and in other sedimentary basins of Canada.

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The physical oceanographic environment on Atlantic Canadian fishing banks

J. W. Loder, C. K. Ross, and P. C. Smith

P. C. Smith. C. K. Ross, and J. W. Loder

A dominant feature of the continental shelf off Atlantic Canada is the widespread occurrence of large and shallow submarine banks. More than 20 banks with horizontal scales exceeding 50 km lie between Cape Cod in the western Gulf of Maine and Cape Chidley at the northern tip of Labrador (see Fig. 1).

These banks have long been of considerable economic importance as the locations of valuable natural resources. Fish stocks in their overlying waters have been the targets of fishing fleets for nearly five centuries. Scientific studies in the present century have shown that banks are often the spawning or nursery areas for particular fish species and that they sometimes have enhanced primary production (microscopic plant growth at the base of the marine food chain) compared to ambient shelf areas. In the past few decades, the identification of valuable hydrocarbons beneath the seafloor has given some banks additional economic potential, although it is accompanied by concerns over the compatibility of hydrocarbon extraction with the maintenance of their rich biological resources. These factors all point to the need to understand the movements and properties of the waters on Atlantic Canadian submarine banks.

During the last three decades, physical oceanographers at BIO have studied a number of these banks. In this article, we describe some important physical characteristics of bank waters, with specific reference to four banks which have been the focus of coordinated fisheries and physical oceanographic investigations: Flemish Cap, the Southeast Shoal of the Grand Bank, Browns Bank, and Georges Bank.

Early studies

Physical oceanographic studies of Atlantic Canadian banks have been conducted for about a century, particularly on the Labrador and Newfoundland shelves by the International Ice Patrol and in the Gulf of Maine by both American and Canadian investigators. The early studies focussed primarily on variations in water temperature and salinity (the properties

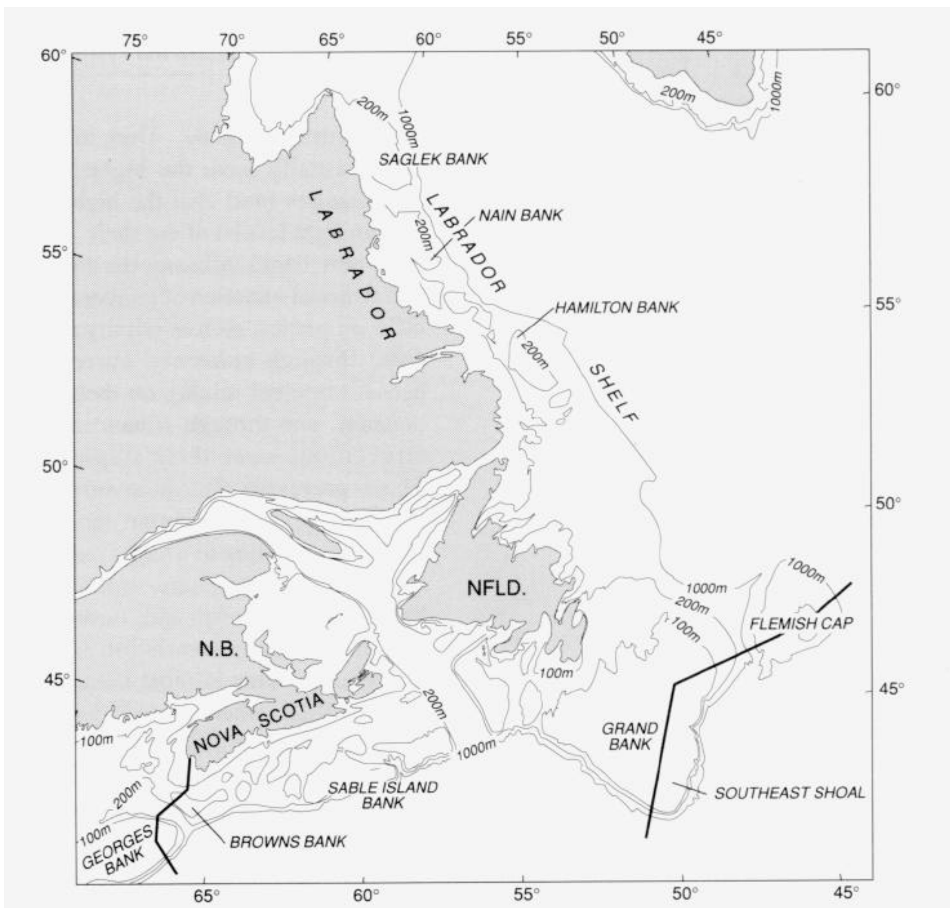

Figure 1. Bathymetric map of the continental shelf off Atlantic Canada showing the series of banks along the outer shelf. The straight-line segments indicate the positions of the temperature sections in figures 2 and 3.

which determine water density). The patterns of currents were estimated mainly from density distributions using the then-new "dynamic height" method, as well as drift-bottle recoveries.

Such studies have revealed that the dominant temporal variation of water temperature over the Atlantic Canadian shelf is a seasonal warming of the upper 100 m or so by solar and atmospheric heating during spring and summer, followed by fall and winter cooling. For the four banks of focus here, this variation is illustrated in figures 2 and 3, which show the mean temperature distributions in March and August on vertical sections across the banks. In March, after winter cooling, the water temperatures over the shelf are relatively uniform, with values near 4°C on Flemish Cap and Browns and Georges banks, and near 0°C on the Grand Bank. By August, near the end of the period of net heat input, a pronounced warming has occurred: 10°C or more near the surface and smaller amounts at depth.

This seasonal temperature variation is an important aspect of the physical environment on banks. For the near-surface waters, the seasonal variations over banks and the surrounding shelf are qualitatively similar. However, because banks extend closer to the sea surface, their near-bottom waters generally undergo greater seasonal warming (and wintertime cooling) than

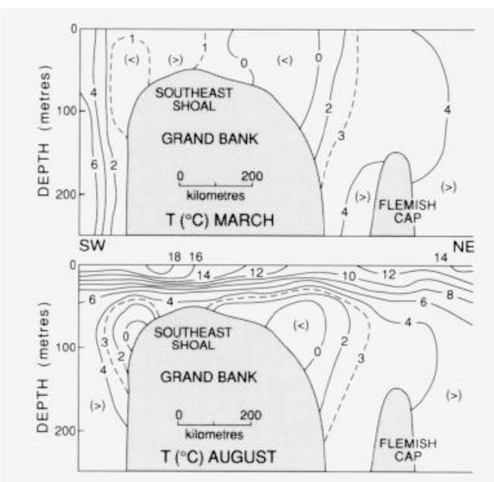

Figure 2. The mean distributions of temperature in March and August on a section across Flemish Cap and the Grand Bank, including the Southeast Shoal (see fig. 1 for location). The distributions are obtained from the monthly means for subareas of various sizes.

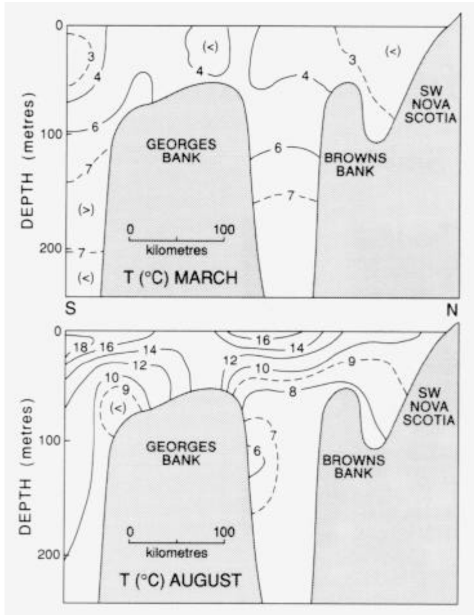

Figure 3. The mean distributions of temperature in March and August on a section across Browns and Georges banks. Because the distributions are obtained from monthly means for subareas of coarse scale in some cases, some features of the temperature field (e.g., reduced stratification over Browns Bank) are not resolved.

those in deeper regions. Thus, in summer, banks usually have the highest bottom temperatures (and also the highest near-bottom light levels) of the shelf.

In turn, banks *influence* the distribution and seasonal variation of temperature (and other properties, such as salinity and nutrients) through enhanced currents and, hence, turbulent mixing on their shallow plateaus, and through enhanced vertical circulations over their sloping sides. These processes distribute surface heat through the water column more effectively, contributing to a slight reduction in the seasonal temperature variation of the banks' surface waters and, further, to the amplified seasonal variation in bottom temperature. This is most noticeable for Georges Bank, where the turbulence levels are high enough to maintain vertically uniform temperatures year-round (Fig. 3). In contrast, there is little seasonal variation in bottom temperature over the much deeper Flemish Cap (Fig. 2). Thus, although there is qualitative similarity in the seasonal temperature variation on banks, there are significant quantitative differences associated with different latitudes (and, hence, surface heating rates), water depths, current regimes, and offshore water masses.

Recent studies

During the past few decades, technological advances have yielded instruments which can be moored for many months to record currents, temperature, and salinity with increasing temporal resolution. Such moored measurements have been the physical oceanographic cornerstone of interdisciplinary field studies on the four banks of interest here. These studies include: the Flemish Cap International Experiment, from 1979-81, which examined recruitment variability in cod and redfish; an investigation, from 1986-89, of larval capelin distributions and variability on the Southeast Shoal; the Southwest Nova Scotia Fisheries Ecology Program, from 1983-85, which examined haddock recruitment variability on Browns Bank; the Georges Bank Larval Herring Patch Study, in 1978; and the Georges Bank Frontal Study, in 1988, which examined primary production and larval distributions.

During these studies, current meters with temperature and (sometimes) salinity sensors were typically deployed at two to five vertical positions at three to six different sites. The deployment sites were generally chosen to be either in the vicinity of known spawning areas or in locations suitable for investigating previously suggested circulation features (such as clockwise residual gyres) and their influence on larval drift. The mean currents observed at these sites, averaged over the entire measurement period (at least one month) and the different vertical positions, are shown in figure 4, together with those from other (U.S.) field programs on Georges Bank. For Flemish Cap and Browns and Georges banks, the measurements have confirmed that the mean currents are largely parallel to isobaths directed in a clockwise sense around the banks. On the other hand, while a branch of the Labrador Current results in a southward mean flow along the eastern side of Southeast Shoal, the moored measurements indicate a weak westward drift over the shoal instead of the previously suggested gyre. Theoretical and numerical modelling studies at BIO have revealed that these current patterns arise primarily from the earth's rotation and weak bottom friction acting on the Labrador Current (for the Newfoundland Shelf banks), and from a "rectification" of the strong tidal currents over the Gulf of Maine banks.

The most important result from the moored measurements, however, is the detailed quantitative information on the temporal variability of the currents at the measurement sites. A bulk measure of the current variability is the standard deviation of each current component about the means that were depth-averaged in figure 4.

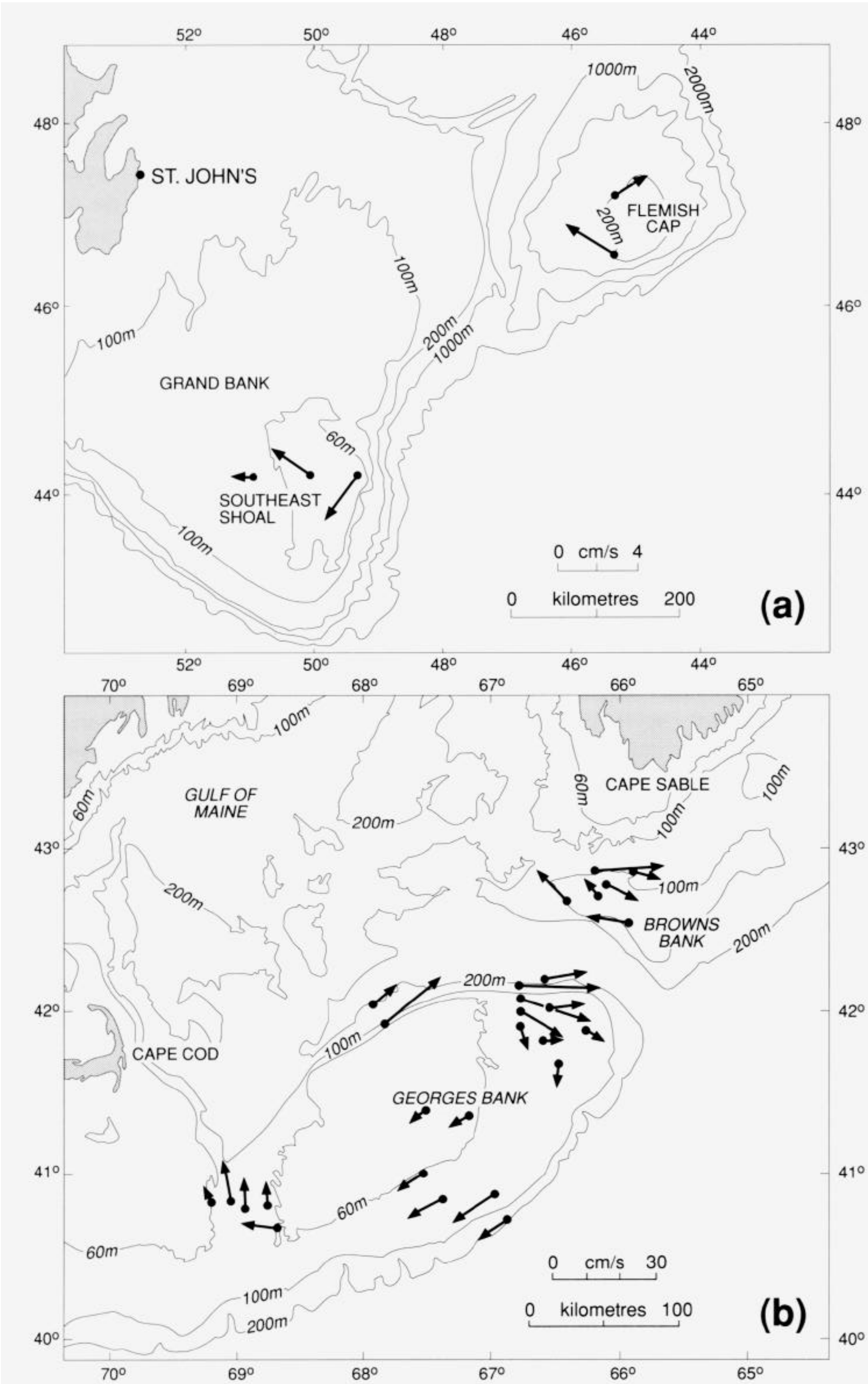

Figure 4. Depth-averaged mean currents from moored measurements of at least one month duration on (a) Flemish Cap and Southeast Shoal, and (h) Browns and Georges banks. Note that the distance and velocity scales are different in (a) and (b).

In figure 5, two types of current standard deviation are displayed for mid-depth current records from each of the banks: the "total current standard deviation" for records with a 1-hour sampling interval, and the "low-frequency current standard deviation" for the same records (subsampled at 6-hour intervals) after low-pass filtering has removed fluctuations with periods less than about 30 hours. The standard deviations are shown for the along-bank (parallel to the bank edge) and cross-bank (perpendicular to the bank edge) components of current.

The first point to note is that the total

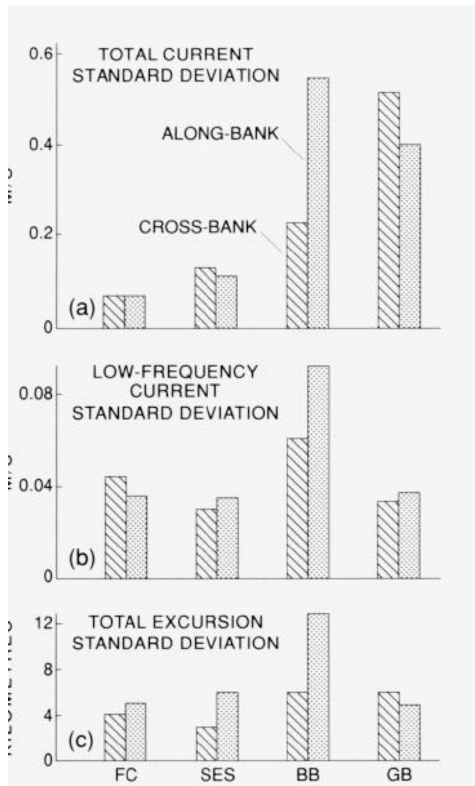

Figure 5. Current and excursion standard deviations for selected mid-depth records on Flemish Cap (FC), Southeast Shoal (SES), Browns Bank (BB), and Georges Bank (GB). The current standard deviations are shown for (a) records with a sampling interval of 1 hour (total current standard deviations), and (b) low-pass filtered records with a sampling interval of 6 *hours (low-frequency current standard deviations). The total excursion standard deviations (c) are for the l-hour records. The standard deviations for both the along-bank and cross-bank directions are shown.*

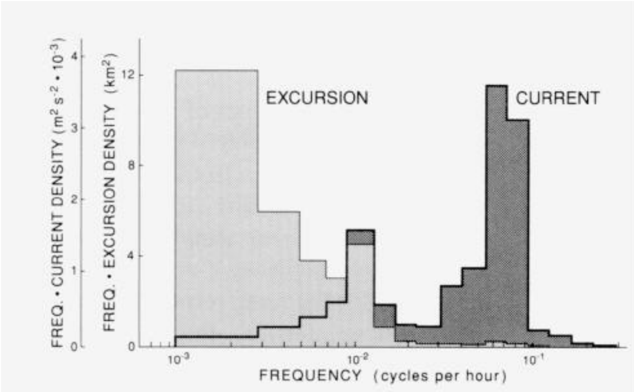

Figure 6. Frequency spectra for the cross-bank current component near mid-depth on Flemish Cap and the associated water-parcel excursions. The spectra are shown in variance-conserving format so that the area under any histogram segment is proportional to the variance in that frequency band (frequency expressed in units of cycles per hour).

current standard deviations (Fig. 5) are generally several times the mean current magnitudes (Fig. 4), so that the instantaneous currents affecting short-term drift are dominated by fluctuating currents rather than the mean pattern. This is true for both the Newfoundland Shelf and the Gulf of Maine banks, although the magnitudes of both the mean and fluctuating currents are typically several times larger in the Gulf of Maine. The standard deviations for the along- and cross-bank directions are generally of comparable magnitude, so that the cross-bank fluctuating currents are particularly dominant over their mean counterparts.

Second, the low-frequency standard deviations are considerably smaller than the total standard deviations on all four banks and are nearly an order of magnitude smaller on Georges Bank. Thus, most of the current variance (the standard deviation squared) on these banks is associated with fluctuating currents in the “tidal band”, with periods between 12 and 24 hours. In fact, most of the variance is associated with the semidiurnal (half-day period) tides, particularly in the Gulf of Maine and the Bay of Fundy, where these tides are in near-resonance.

Finally, although weaker than the tidal-band currents, the low-frequency currents are very important to the longer-term drift of water parcels. This is because their longer periods generally result in larger horizontal displacements of the water parcels, as illustrated (Fig. 6) by frequency spectra for the cross-bank current and associated water-parcel excursions on Flemish Cap. These spectra show the relative contributions, to the current and excursion variance, of sinusoidal variations with periods between 2 hours and 21 days. Although current variations with periods near l/2 and 4 days are the most energetic, the largest excursions are associated with the longest-period (lowest-frequency) variations resolved in the spectra. As a bulk measure of the excursion variability, the “total excursion standard deviation” can be computed as the square root of the total variance in the excursion spectrum. It can be interpreted as an average amplitude for horizontal displacements by current fluctuations of all periods resolved in the spectrum. The excursion standard deviations for the selected mid-depth records from all four banks are included in figure 5, showing relative magnitudes similar to the low-frequency current standard deviations. These standard deviations have magnitudes between 3 and 13 km, corresponding to typical excursions of 6 to 26 km. Of particular note is the occurrence of the largest excursions on the smallest of the four banks - Browns Bank - suggesting that it has the most effective horizontal exchange with surrounding waters.

These aspects of the current structure on Atlantic Canadian banks are only examples of the quantitative information which can be obtained from the moored measurements. The currents and associated excursions have both horizontal and vertical structure, which are also important to water-parcel drift, and current fluctuations in particular frequency bands can be described in detail and quantitatively related to their driving forces. Moored measurements of temperature and salinity similarly provide a wealth of detail not obtainable from ship-based surveys.

A time-scale characterization of circulation and mixing on banks

The moored and other current measurements in the recent field studies provide detailed quantitative information on circulation and mixing over banks, indicating strong spatial and temporal variability. One approach to identifying possible influences that the physical environment has on the biological organisms and processes on banks is to compare key characteristics of the physics and biology for indications of corresponding variations. Such characteristics must be representative of the banks and their ecosystems, yet account for variability on the (often small) space and (short) time scales on which physical-biological interactions occur.

For circulation and mixing over banks, a simple and relevant characterization involves the time scales for exchange in three perpendicular directions: the around-bank direction following isobaths, the cross-bank direction perpendicular to isobaths, and the vertical. For the gyre-like residual flow in the around-bank direction, a “recirculation time” can be defined as the time required for a water parcel to make a complete circuit of the bank. Its statistics can be estimated from moored current measurements (with assumptions about the currents between mooring sites) or, more appropriately, from satellite-tracked drifters which have been used to complement the moored measurements in most bank studies. For cross-bank exchange, a “residence time” can be defined as the time required for displacement from the bank of some fraction of its total water volume. Its determination is often more difficult, but estimates can be obtained from drifters, moored current measurements, and heat or salt budgets. Finally, for vertical exchange, a “vertical-diffusion time scale” can be defined as the time required for the vertical redistribution of passive material over some specified distance such as the water depth or the thickness of the thermocline. Although qualitative information on this scale is sometimes available from water property distributions (e.g., Figs. 2 and 3) and estimates can be obtained using moored current and hydrographic measurements, this scale is often the most difficult to determine accurately, as it requires special instruments which resolve some portion of the turbulent fluctuations.

The statistics of these time scales provide a concise quantification of the significance of particular current components in relation to currents in other directions and frequency bands. For example, the significance (to water-parcel drift) of any around-bank residual gyre clearly depends on the length of time that water parcels stay in the region of gyre-like circulation or over the bank. This significance can be assessed through comparison of the associated recirculation time with the bank's residence time and vertical-exchange time scale. In the limit of the residence time being much shorter than the recirculation time (i.e., relatively fast cross-bank exchange), due perhaps to energetic fluctuating currents, a residual gyre may be of little significance to long-term drift even though moored measurements may indicate around-bank mean currents which are significantly different from zero.

The results of the recent field studies on the four Atlantic Canadian banks can be used in this time-scale characterization to provide a simple quantitative description of their circulation and mixing regimes. This is summarized schematically in figure 7, where each bank is represented by a two-layer cylinder approximating the thermal and density stratification present for much of the year. The description is summarized using arrows for recirculation, residence, and vertical exchange, with the area of each arrow chosen as being inversely proportional to the associated time scale (or proportional to an associated rate), normalized by the residence time; i.e., the schematics illustrate the recirculation and vertical-exchange times relative to the residence time for each bank. As hinted earlier, and as somewhat expected from the variation in horizontal extent of the different banks (Fig. 4), there is actually a considerable variation in present estimates of the residence times: from the order of 10 days on Browns Bank to 50 days or more on Flemish Cap, Southeast Shoal, and Georges Bank.

On Flemish Cap, the vertical-exchange time scale is generally much longer than the residence and recirculation times, such that materials entering the cap in the upper or lower layer can be expected to leave in that layer. The recirculation time is longer than the residence time, such that water parcels are not expected to make complete circuits of the cap.

On Southeast Shoal, the available information indicates that the residence time and vertical-exchange time are of similar magnitude, and there is no mean gyre. In contrast, the vertical-exchange time scale on Browns and Georges banks is generally much shorter than the residence and recirculation times, implying considerable vertical redistribution of materials through the water column while over these banks.

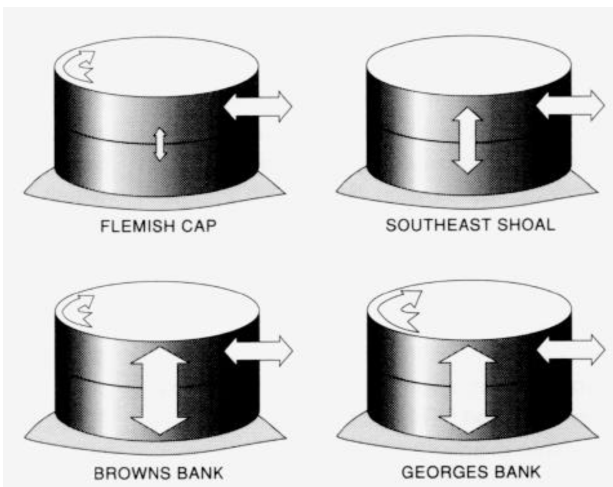

Figure 7. Schematic summary of the recirculation and vertical exchange times, relative to the residence time, on the four banks.

For Browns Bank as a whole, the residence time is shorter than the recirculation time, although for its western cap the two times have comparable magnitudes consistent with frequent complete circuits by drifting water parcels. For Georges Bank, the annual-average residence and recirculation times are comparable, but there is a seasonal variation, with the recirculation times in summer being shorter than the residence times. This suggests that the residual clockwise gyre on Georges Bank is of greater significance to long-term water-parcel drift than elsewhere.

Of course, this characterization is only a small step toward a relevant quantitative description of the physical environment on Atlantic Canadian banks. Further observations and analyses are required in order to obtain more reliable statistics on the important time scales and to resolve their seasonal and other variations; the important physical processes need to be understood in order to enhance our descriptive and predictive capabilities; there are other banks which have economic importance but for which few oceanographic data currently exist; and the influences of the physical environment on biological organisms and processes need to be identified and understood.

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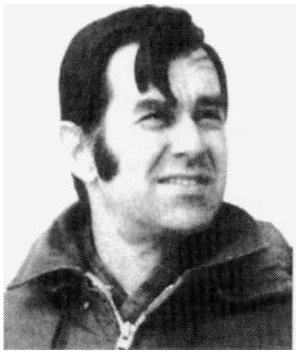
Humidity exchange over the sea: The HEXOS program

S. D. Smith



S. D. Smith

The evaporation process is a major component of weather and climate. Most of the water vapour supplied to the atmosphere originates from the 71% of the earth's surface which is covered by oceans. The associated latent heat flux is an important term in the global energy budget and, in particular, is the major source of energy for storms at sea. Evaporation leaves behind water that is more saline and denser, and the formation of water masses at the surface drives thermohaline circulation in the ocean. A good understanding and a quantitative model of evaporation processes are needed in a wide range of oceanographic and meteorological problems, from daily weather forecasting to the modelling of climate change, and from local to global scales. It may, therefore, come as a surprise to the reader to learn that only a handful of direct measurements of evaporation from the open ocean are reported in the literature, and that none of these was taken in high winds (Smith, 1989).

Measuring evaporation from the sea surface

Because of surface waves, we cannot isolate and weigh a sample of the sea surface to directly measure evaporation. Suppressing the waves or placing an evaporation pan on the deck of a ship would alter the dynamics and so would not produce valid results. The most direct method available is to measure the vertical transport of water vapour in the atmospheric boundary layer at a level a few metres above the surface; this flux is equal to the evaporation rate if we neglect the rate of storage of water vapour due to changes in the humidity of the intervening air layer. Two mechanisms transport water vapour from moister to drier layers of air: diffusion, and turbulent mixing. Diffusion is significant only in a surface microlayer which is a fraction of a millimetre thick. In stormy conditions, we must also consider the vertical transport of spray droplets, which can carry liquid water upward to evaporate at a higher level.

The eddy correlation method directly measures the vertical flux of water vapour and of other gases, as well as the heat and momentum in the atmospheric boundary layer. The density of water vapour at a fixed measuring point can be separated into mean and fluctuating components, $\overline{\rho_v}$ and ρ_v' respectively. The fluctuations occur when saturated air originating at the surface with vapour density ρ_s mixes turbulently with overlying, usually drier air. The wind velocity at the measuring point can also be separated into fluctuations and a mean; the vertical fluctuation component, u_3, transports water vapour up and down past the measuring point, so that the instantaneous water vapour flux is $(\rho_v u_3)'$. The mean water vapour flux, $<\rho_v u_3>'$, which is carried by turbulent eddies, arises from a correlation between humidity and vertical wind. The time required to obtain a stable average, which depends on measurement height (typically 4 to 20 m) and wind speed, is usually in the range of 10 to 60 minutes. The mean upward flux arises from apparently random fluctuations because updrafts tend to bring moister air up from near-surface layers, while downdrafts tend to carry drier air down from above. If warm, moist air lies over cold water $(\rho_s < \rho_v)$, it is possible to observe a downward (condensation) flux.

In order to make eddy correlation measurements of evaporation, we need sensors for turbulent fluctuations of humidity and vertical wind, a fixed support for these sensors which does not excessively distort the wind turbulence, and a system to log and analyze time-series data. The required frequency response (typically 5 to 10 Hz) and data sampling rate also depend on the height of measurement and on wind speed. Portable computers have largely solved the data-handling problem, but other difficulties remain. A ship does not make a good platform because of its flow distortion and its motion with the waves, and most existing measurements are made from towers or platforms located in shallow coastal waters.

A less direct method is the "dissipation" technique, which estimates evaporation from measured spectra of fluctuations in humidity, temperature, and horizontal wind velocity (e.g., Fairall and Larsen, 1986). This method involves assumptions about the structure of boundary-layer turbulence, which need to be tested, but is much less vulnerable to errors from flow distortion and vessel motion.

Both eddy-correlation and dissipation methods require a fast-response humidity sensor. The majority of studies to date have used a Lyman-alpha humidiometer, which senses absorption of the Lyman alpha line (λ = 0.12156 μm) of hydrogen in the water molecule. The absorption is so strong that the path length is only 1 to 3 cm and ambient (solar) radiation is entirely negligible at this wavelength. The source and detector tubes require windows of MgF_2 or LiF salt crystals, which are transparent in the far ultraviolet, and because these are soluble in water they must be protected from dew or salt spray. Until recently, these devices had been used successfully in the marine environment only in light to moderate wind and sea-state conditions. Other rapid-response humidity sensors include fine-wire wet-and-dry thermocouples, microwave refractometers, and, recently, infrared absorption sensors which can use insoluble quartz windows. All of these sensors, in their present state of development, require expert care and attention if they are to produce reliable data.

Because eddy-correlation and dissipation measurements of evaporation require special effort and resources, most studies of evaporation and latent heat flux will have to rely on an empirical formula to estimate evaporation from "bulk" quantities which can be routinely measured or modelled, such as humidity, sea-surface temperature, wind speed, and sea state. It therefore becomes necessary to measure these supporting parameters in addition to the evaporation.

The HEXOS program

The Humidity Exchange over the Sea (HEXOS) program originated at BIO in 1981 with a NATO-sponsored workshop (Smith and Katsaros, 1981). This workshop convened specialists from around the world who summarized the state of current knowledge. In so doing, they recognized serious deficiencies in experimental and theoretical descriptions of evaporation from the sea surface, and posed a series of six questions which needed to be answered:

(1) How does the coefficient C_E in the "bulk" formula for vapour flux $E = C_E(\rho_s - \rho_v)U_r$ depend on wind speed, sea state, and stratification? Here ρ_v and ρ_s are the vapour densities at a reference height above the surface and in equilibrium with water at the sea-surface temperature. U_r is the mean wind speed at the reference height.

(2) Can the above formula be applied at high wind speeds, and, if so, at what reference height should the humidity be measured?

(3) Can an expected dependence of evaporation on wind stress, stability, wave breaking, and spray droplet distribution be demonstrated experimentally?

(4) How well can dissipation measurements from a ship or a fixed platform estimate evaporation from spectra of wind and humidity fluctuations?

(5) Can eddy-correlation measurements of humidity and vertical wind fluctuations at a fixed platform be satisfactorily corrected for flow distortion by the platform?

(6) Can fast-response humidity sensors be made to operate in the marine environment for extended periods of time? Could they be adapted for longer-term operation on unmanned platforms?

The first three questions address the problem of modelling the evaporation rate in terms of more easily and routinely measured parameters. The remaining questions relate to experimental methods and techniques.

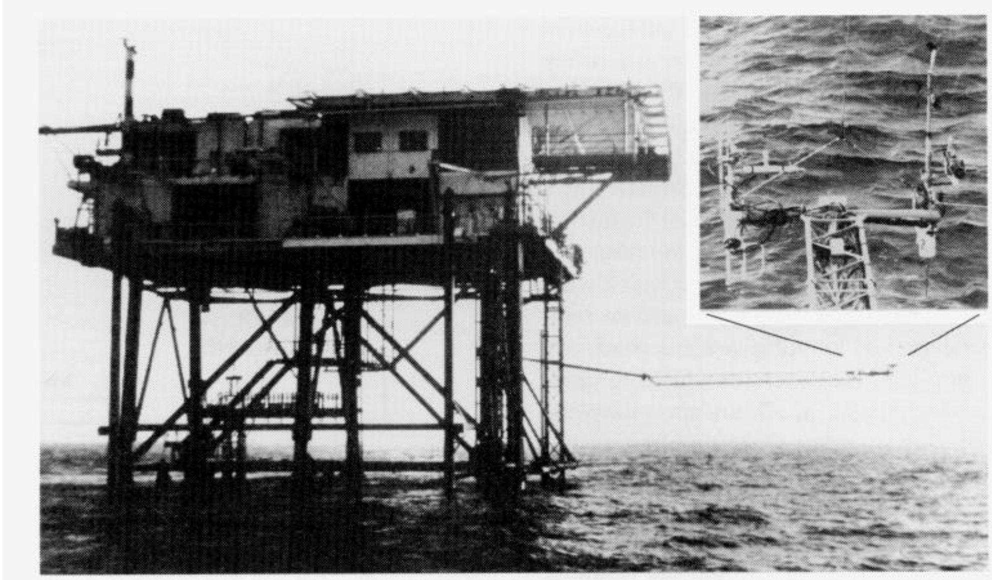


Figure 1. Meetpost Noordwijk with turbulence sensors deployed on boom during 1984 HEXOS Pilot Experiment.

The 1981 HEXOS Workshop and subsequent discussions laid the foundations for the HEXOS Scientific Plan (Smith et *al.*, 1983). This plan was built around the availability of Meetpost Noordwijk (MPN), a research platform off the Dutch coast in the North Sea, and of a large air-sea interaction simulation tunnel at Luminy, France. It proposed the following series of coordinated experiments to work toward answering the above questions.

Flow Distortion Study: At the outset it was not known how flow distortion caused by the structure of the MPN would influence the measurements (see question 5, above). A 1:25 scale model was tested in a boundary-layer wind tunnel at British Marine Technology Ltd. (Wills, 1984). This study demonstrated the feasibility of eddy-flux measurements at a boom extending 16 m upwind from the platform and simulated the influence of the structure on the measured wind velocity.

HEXOS Pilot Experiment: A 20 m boom (Fig. 1) was constructed to support turbulence sensors and other types at a distance of 16 m from the west side of the MPN, in accordance with recommendations of the flow distortion study. A pilot experiment, conducted from October 29 to November 23, 1984, tested the feasibility of eddy-flux, droplet-distribution, and related measurements made by several groups at the MPN (Oost *et al.,* 1984; Katsaros *et al.,* 1987). During this experiment, a group from BIO measured evaporation by the eddy-correlation method, using a Lyman alpha hygrometer in a newly designed aspirated shield which removed water droplets from the airstream before it reached the windows of the sensor; a sonic anemometer was also used to measure wind turbulence. For comparison, a propellor anemometer was mounted on the boom by a group from the University of Washington (UW) and a pressure-port anemometer was operated by the Royal Netherlands Meteorological Institute (KNMI). Aspirated fine-wire dry-bulb and wet-bulb thermocouples were used by UW to measure humidity and temperature fluctuations. Oceanic whitecaps were analyzed from video-tape recordings, and aerosol particle concentrations, size distributions, and fluxes were studied using optical counters and inertial impact collectors. On November 21, 1984, a flight of the C-l 30 Hercules aircraft of the British Meteorological Office (BMO) was made to study the possible contribution of aerosol spray droplets to the height distribution of turbulent humidity flux in the atmospheric boundary layer.

HEXOS Studies in a Simulation Tunnel (HEXIST): This component of the HEXOS program aims to develop models that describe the production and fate of spray droplets generated by the air bubbles that are entrained by breaking waves when they burst at the sea surface, and the contribution of these droplets to the humidity flux. The model formulations are based on experiments in the Grande Soufflerie, a wind-wave simulation tunnel at the Institut de mécanique statistique de la turbulence (IMST), in Luminy, France, in which wind speed, surface waves, water and air temperature, and humidity are independently controlled. The processes which are simulated are: the surface flux of spray droplets; turbulent transport of the droplets; evaporation of the droplets; interaction of the evaporating droplets with the turbulent fields of wind, temperature, and humidity, as well as with waves; and the resulting enhancement of humidity flux (Mestayer *et al.,* 1989).

A series of HEXIST measurements was based on the simulation of a single whitecap, about 1 m^2 in area, by means of a submerged "bubbler" array of ceramic aquarium aerators. This reproducible, local source of aerosol droplets was placed at various distances from the probes during separate sets of measurements of the effects of turbulent transport and diffusion, and of evaporation, on the droplet concentrations. Evaporation was monitored by the demand on the tunnel controls to maintain the air temperature and dew point (Mestayer and Lefauconnier, 1988). The behaviour of the evaporating droplets during the HEXIST 1 experiment (June 1985) has been simulated using a Lagrangian model of droplet trajectories (Edson *et al.,* 1988). The effects of evaporation of droplets on the water vapour and temperature fields were observed during HEXIST 2 (July 1985).

HEXOS Main Experiment (HEXMAX): HEXMAX, which took place in October and November of 1986 in the vicinity of the MPN (Fig. 2), was a culmination of the three previous experiments, with participation from 15 institutions in 7 countries (Smith *et al.,* 1990).

Before HEXMAX, the boom on the MPN was rebuilt and strengthened to withstand higher wind loads. The three groups from the pilot experiment deployed improved eddy-flux systems, and the HEXIST group installed dissipation packages, both on the boom (for direct comparison with eddy-correlation measurements) and on a 7 m mast on the helicopter deck of the MPN, where flow distortion effects were expected (in order to test the relative insensitivity of this method to these effects). The distribution of aerosol droplets with size and height was measured (de Leeuw, 1989), and the chemical composition of aerosols was studied. Wave elevations were measured and video tapes were recorded to obtain whitecap statistics.

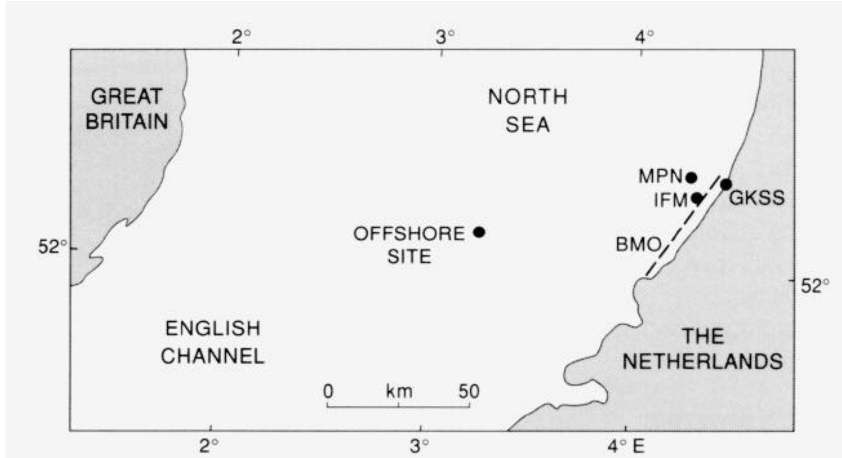


Figure 2. The HEXMAX area: the offshore site of the R.R.S. Frederick Russell; *the flight path of BMO's C-130 Hercules aircraft (broken line); the site of the GKSS radiosonde, tethersonde, and profile tower; the IFM's tripod; and Meetpost Noordwijk (MPN).*

During HEXMAX, the R.R.S. *Frederick Russell* operated alternately in two areas: a site close to the MPN, and an offshore site with slightly deeper water (Fig. 2). Data from the offshore site gave important information about the possible influence of shallow water (16 m) and proximity to shore (10 km) on fluxes at the MPN. Measurements taken on the *Frederick Russell* included dissipation estimates of evaporation, heat flux, and wind stress; aerosols; solar radiation; routine meteorological and oceanographic observations; sea state; and radiosondes (Taylor, 1987). A group from the Institut für Meereskunde (IFM) at Kiel University installed a tripod on the seabed halfway between the shore and the MPN (Fig. 2); this was set in a water depth of 15 m and had an 8 m mast which carried instruments to measure wind, heat, moisture, and waves. A three-propeller anemometer and a fast-response psychrometer were used to measure momentum, heat, and moisture fluxes. Another German group, from the GKSS Research Centre in Geesthacht, mounted a 15 m mast on the beach, launched radiosondes, and flew instruments on the tether of a kite or tethered balloon to get profiles of wind, temperature, and humidity from ground level to a height of 450 m. Favourable weather resulted in almost continuous data collection at all stations from October 19 onward.

To study the variation of humidity with height, the data from radiosondes and tethered balloons were supplemented by four flights of the C-130 Hercules of BMO's Research Flight Facility on October 22 and 29 and November 18 and 20. The instruments aboard the aircraft measured the wind vector, air temperature and humidity, turbulent fluxes of momentum, heat and moisture, the radiative sea-surface temperature, and aerosol droplet spectra to give a three-dimensional snapshot of the structure of the atmospheric boundary layer.

Preliminary analysis indicates that drag coefficients at the MPN increase with wind speed, as expected from previous experiments at similar sites, and are significantly higher than Smith's (1988) formula for deep water. Evaporation coefficients derived using data from BIO Lyman alpha humidiometers and the KNMI sonic anemometer do not increase significantly with wind speeds up to 18 m s^{-1}; nor do UW evaporation coefficients calculated from measurements made with a thermocouple psychrometer or a Lyman alpha humidiometer and a KGill anemometer increase significantly with increases in wind speed. Taken together, these results suggest that the value CEN = 1.2 x 10^{-3}, given in a recent review paper (Smith, 1989), may be extended to a wind speed of 18 m s^{-1}.

One-Dimensional Stationary Aerosol Boundary Layer (CLUSE): In a second series of HEXOS experiments conducted in the IMST simulation tunnel in 1988 and in the Whitecap Simulation Tank of the University of Connecticut in 1988 and 1989, a network of underwater air bubblers generated aerosols by the bursting of bubbles, while aerosol and flux measurements were made at predetermined wind, temperature, and humidity conditions (Smith *et al.*, 1990). The acronym CLUSE is derived from the French title of the study, "Couche limite unidimensionelle stationnaire d'embruns". The new series of simulation experiments has been undertaken in parallel with the development of numerical models of the local interactions between the droplet distribution and the turbulent flow. A horizontally homogeneous source of droplets was obtained by suspending a spray-bubbler array in nets at a depth of 50 cm over a 22 m fetch. With a larger and homogeneous surface flux of droplets, there were stronger interactions with the turbulent fields of humidity, temperature, and velocity. CLUSE consisted of a main simulation experiment and a series of four smaller experiments aimed at developing particular techniques. Eight groups participated in these experiments.

HEXOS Modelling and Parameterization: A quantitative description of water transfer, including the detailed modelling of the diffusion of droplets by turbulence and of their evaporation in the turbulent flow field, is a primary goal of the entire HEXOS program. Advances in this area will be based on interpretation of the HEXOS experimental results, together with theory and other published data. Several products are anticipated: a "bulk" parameterization based on data at higher wind speeds than previously available; a steady-state, one-dimensional model for the surface layer, which will incorporate turbulent fluxes, vertical-humidity and aerosol droplet gradients, and the evaporation of droplets; and, possibly, more complex models of the distributions of droplets, turbulence, and fluxes extending through the atmospheric boundary layer.

HEXOS organization

A fairly large international program has been carried out as the result of the participation of groups from a number of institutions and their funding agencies. The NATO Science Division has supported several workshops and some travel. The program is coordinated by the HEXOS Scientific Committee, consisting of K.B. Katsaros, W.A. Oost, S.D. Smith, and (since 1988) P.G. Mestayer. Oost organized the HEXOS Pilot Experiment and HEXMAX, and Mestayer hosted the HEXIST and CLUSE experiments. A HEXOS newsletter is distributed from time to time to keep all participants up to date; there have been 11 issues so far. This rather informal structure has succeeded because of the cooperative and enthusiastic attitudes of the many participants who have combined their expertise to focus on evaporation processes.

Conclusion

The HEXOS program has stimulated research on one of the most complex processes in the marine boundary layer - the flux of vapour and spray droplets from sea to air. The main experiment, HEXMAX, was successful for several reasons: careful preparation, long periods of ideal weather, and knowledgeable technicians and scientists in the field. The collaborative work of many scientists resulted in a more complete data set than any one group could have produced. The HEXIST-CLUSE work conducted in the controlled environments of a wind-wave simulation tunnel and a whitecap simulation tank helped us to understand the interaction and feedback between vertical water flux caused by surface evaporation and that caused by spray droplets. Predictions based on theoretical calculations and extrapolations from early laboratory work show large increases in C_E at wind speeds above 15 m s^{-1} due to the effects of sea-spray on air-seawater flux (Ling and Kao, 1976; Bortkovskii, 1987). These have not been borne out by our measurements. We currently attribute the lack of a large spray effect on the measured net water-vapour flux to negative feedback on the surface evaporative component through a decreased water-vapour density gradient near the surface. This contention is also supported by the laboratory results. Much modelling work will be needed to fully explain these measurements, and several approaches are currently being pursued.

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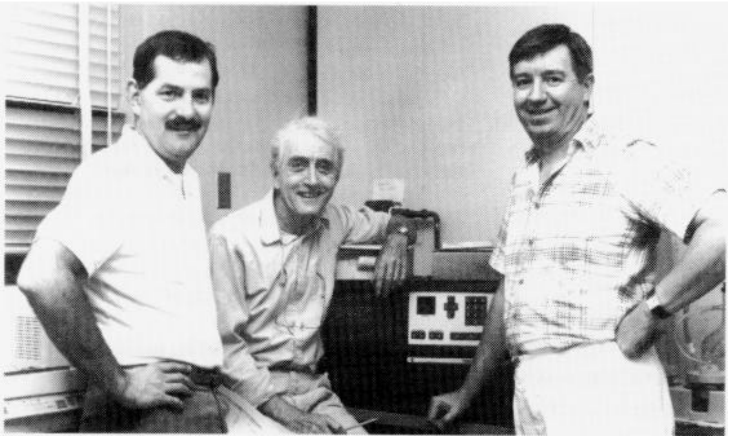
The JGOFS Atlantic pilot study, 1989

A. R. Longhurst, T. Platt, and W. G. Harrison



W. G. Harrison, A. R. Longhurst, and T. Platt

During April and May 1989, a large biological oceanographic group from the Department of Fisheries and Oceans (DFO) was at sea in *Baffin,* working in co-operation with foreign oceanographers aboard ships and aircraft from the U.K., the U.S.A., Germany, and The Netherlands. Altogether, about 15 ship-months were spent in the North Atlantic from April to October to test the feasibility of measuring - on the scale of the whole ocean basin-the biological uptake of carbon dioxide from the atmosphere over the North Atlantic.

These voyages were the first to be mounted under the Joint Global Ocean Flux Study (JGOFS), which is coordinated by the Scientific Committee on Oceanic Research (SCOR, an arm of the International Council of Scientific Unions) from its office at Dalhousie University. The mounting of JGOFS itself is one of the first fruits of the revolution in biological oceanography brought about by the recent availability of worldwide data on ocean colour revealed by satellite sensors. This allows us for the first time to view the growth of plants everywhere in the oceans almost simultaneously.

The growth of land plants and of marine algae (including single-cell oceanic phytoplankton) is achieved by the incorporation of carbon originating as atmospheric carbon dioxide. Global rates of plant growth, either on land or in the sea, have not yet been satisfactorily measured, but plant growth is thought to be a major component of global carbon flux and is thus of significance to problems of global climate change and the greenhouse effect. Studies of past climate change, as indicated by the geological record, especially for the Pleistocene glaciations, now suggest that changes between glacial and interglacial climates occurred much more rapidly than previously thought. Such rapid climate changes, associated with rapid changes in atmospheric carbon dioxide, could probably only have occurred if equally rapid changes in the growth of marine plants also occurred in response to changes in wind strength at the sea surface; this response of marine plants, causing them to rapidly draw down more carbon dioxide from the atmosphere, has come to be known as the "phytoplankton multiplier" effect.

The failure of biological oceanographers to quantify confidently the global rate of plant growth in the oceans, and hence the rate of draw-down of CO_2 from the atmosphere, has been due almost entirely to undersampling. Comprehensive data representing plant growth on the scale of whole oceans are simply too expensive to be obtained by research ships, so our estimates of plant production in the oceans have varied by about 100%.

However, with ocean-colour images from satellites we can now estimate the amount of plant material at the surface over the whole ocean from season to season. Progress has been made, at BIO and elsewhere, in developing algorithms to translate these images into estimates of total plant material and, finally, into estimates of the rate of plant growth. Together with deployment of sediment traps in critical locations in the ocean, such information on global plant growth finally gives us a means of estimating the drawing down of carbon from the atmosphere and its sequestration into the deep sea by this mechanism, popularly known as the "biological pump". The central goal of JGOFS, expected to be a major component of international cooperation in biological oceanography during the 1990s, is to exploit these new techniques and to quantify the role of ocean biota in global carbon flux and climate change.

The 1989 Atlantic Pilot Study was intended to obtain experience during an integrated study of the North Atlantic spring bloom, and so to lay the operational basis for the subsequent ten-year JGOFS study. The North Atlantic spring bloom was selected for the pilot study because it is generally predictable in its occurrence and is one of the largest seasonal events in the global sea-surface colour field, a consequence of intense deep mixing during winter.

Ships were to be at sea during the whole period of plant growth, starting in March at 15°N, and were to follow the bloom northward during the summer as far as 72°N (Fig. 1). Intensive pre-cruise planning by a dozen international working groups was required during the preceding year to establish protocols for core experiments to be made by each ship and for formats to be adopted for data exchange. The German vessel *Meteor* was already at work east of the mid-Atlantic Ridge when *Baffin* sailed from BIO in early April to the western part of the ocean. *Atlantis II* (U.S.A.) and *Discovery II* (U.K.) also joined the operation in April, while *Endeavor* (U.S.A.) and *Tyro* (Netherlands) carried the study through to the autumn. The work of all these ships was planned around a series of 5- to 15-day drifter experiments, where process studies of carbon uptake

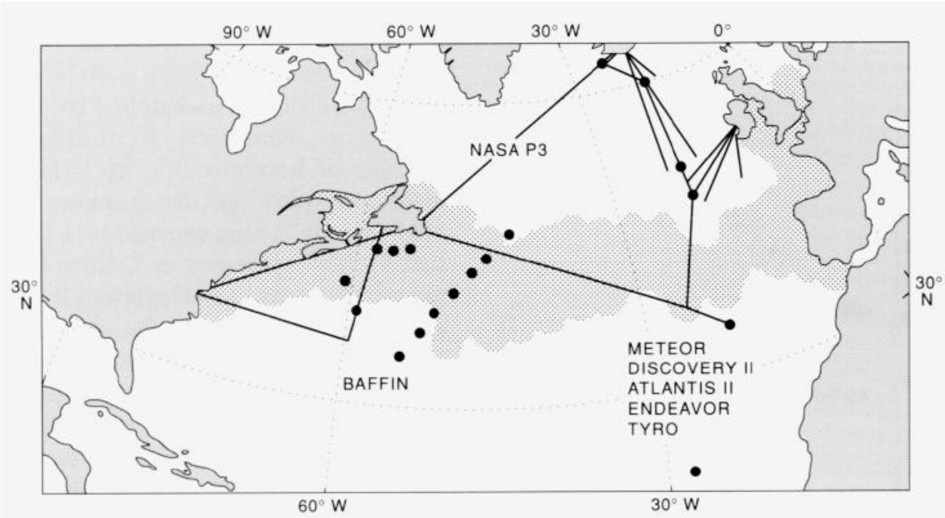


Figure 1. The JGOFS Atlantic Pilot Study, 1989. All Canadian stations are shown, but only the principal stations worked by European ships south of lceland are included. The region anticipated to be covered by the most active spring bloom in April is stippled. The approximate tracks flown by the P-3 aircraft are indicated.

and settlement could be completed, linked by observational sections along the north-south tracks. Especially late in the season, and at the more northerly stations, weather conditions in 1989 were very poor and, hence, limited what could be accomplished.

Extensive low-altitude coverage of the North Atlantic sea surface was also obtained by a NASA P-3 aircraft measuring chlorophyll and other plant pigments, temperature, and both upwelling and downwelling spectral irradiance using LIDAR sensing equipment. Between the U.S. east coast, St. John's, the Azores, Iceland, and the U.K., this aircraft logged many thousand kilometres at an altitude of only 150 m. "Sea truth", required to calibrate the sensors, was obtained by overflying the oceanographic ships in turn, including *Baffin* on 20 April. The whole study was coordinated from a temporary office in Plymouth, England, with which the ships at sea were in constant contact.

Apart from obtaining the only comprehensive ocean-wide set of data on the North Atlantic spring bloom, and testing procedures for future work, the Atlantic Pilot Study produced several unexpected findings about the dynamics of the spring bloom. Perhaps the most significant was obtained by the U.K. team aboard *Discovery II,* who reported by radio on May 23 that sections obtained along their track showed "a very close inverse correlation between algal concentration and pCO_2, thus proving drawdown of CO_2 to be biologically controlled during the spring bloom". *Atlantis II* reported that a late-May gale had recharged the surface layer with nutrients, so sustaining the spring bloom, and that subsurface ammonium distribution showed that much production was being recycled in the upper 100 m rather than sinking to the interior of the ocean. The same ship also reported that, as biological activity and settling of particles increased, so pCO_2 decreased, offering further evidence of the role of the spring bloom in controlling the air-sea flux of CO_2. During June, *Endeavor* was able to locate and study discrete blooms of coccolithophores at 62°N, 10 to 20 km in diameter, identified in near-real-time AVHRR satellite images.

In *Baffin,* BIO scientists arrived at their southerly station (32°N) with all their equipment operational after a rather rough passage from Halifax. This station proved to be in a water mass that had not experienced the normal winter mixing, and no trace of a spring bloom could be found. At this station, which had previously been occupied several times at other seasons by the BIO group, it was surprising to find a more stable situation and smaller amounts of phytoplankton chlorophyll than at any of the previous occupations. Just the opposite had been anticipated for this season.

A section was then worked from 32°N to 47°N (Fig. 2), including two 6-day drifter stations at 40°N and 45°N, respectively, where MULTITRAP sediment

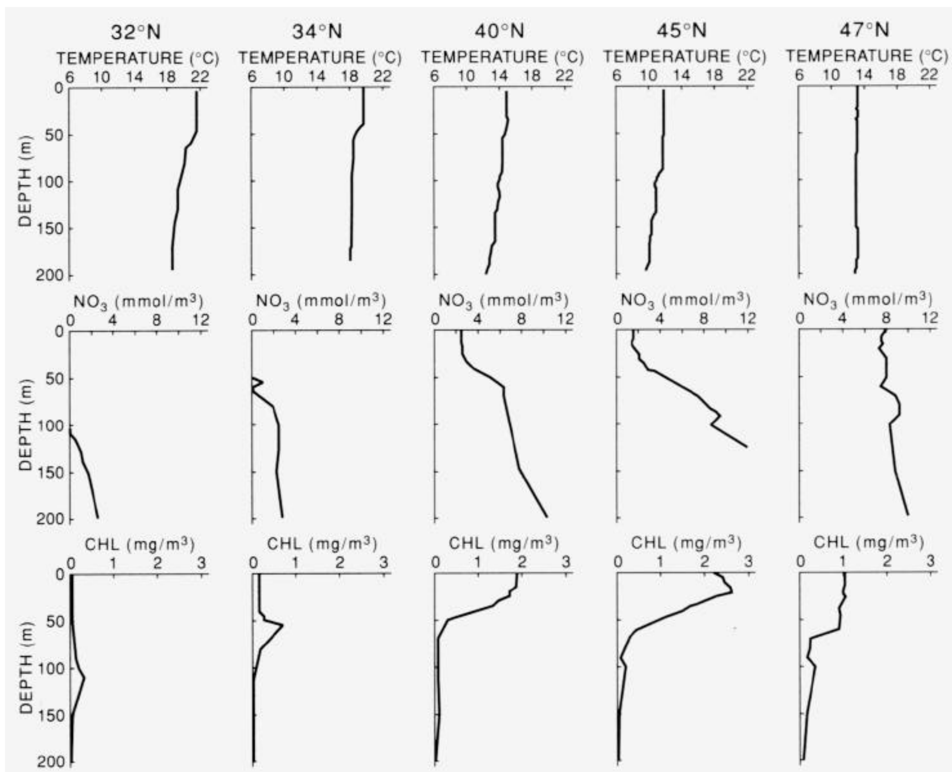


Figure 2. A section of temperature, chlorophyll-a, nitrate, and total particles from 1 to 5 µm, showing the northward development of the spring bloom.

traps were deployed at 150, 250, and 500 m. This section crossed the developing spring bloom, showing it to be progressively less mature toward the north, as indicated by the strength and depth of the chlorophyll maximum and the extent to which nitrate had been stripped from the mixed layer by plant growth.

This initial exploration of the spring bloom of the open ocean showed that, at 40°N, the developing bloom was dominated by very small cells, though the green water contained chlorophyll-a at levels up to 2.8 mg m^{-3} and nutrients (nitrate and silicate-see figure 3) were by no means yet depleted. There were very few diatoms, though these are the “classical” spring bloom cells and were expected to account for most of the ocean colour during the initial stages of the bloom before mixed layer nitrate is exhausted. Actually, nannoflagellates, cyanobacteria, and prochlorophytes from 0.8 to 10.0 µm accounted for most of the measured chlorophyll. These are the organisms expected to follow a diatom bloom after it has exhausted the nitrate available in the mixed layer prior to the bloom.

It appeared that the growth of the population of small photosynthetic cells was being constrained by grazing by microplankton, mostly unicellular; this was shown by experiments on *Atlantis II* at 47°N in the eastern Atlantic and is expected to be confirmed for our station by the results of similar experiments aboard *Baffin*. At this station, carbon export at 150 m was equivalent to 24% of the primary production in the surface layers above.

At 45°N, the situation was more classical, and a mature diatom bloom dominated by *Rhizoselenia* was encountered. However, here the growth of the diatoms appeared not to be constrained by the supply of nitrate, as anticipated from previous studies, but by silicate as the limiting nutrient. Observations that suggested this to be the case were confirmed by silicate limitation in experiments done at this station. This surprising result was also obtained by *Atlantis II* about 1,000 km to the east, so is likely an ocean-wide phenomenon.

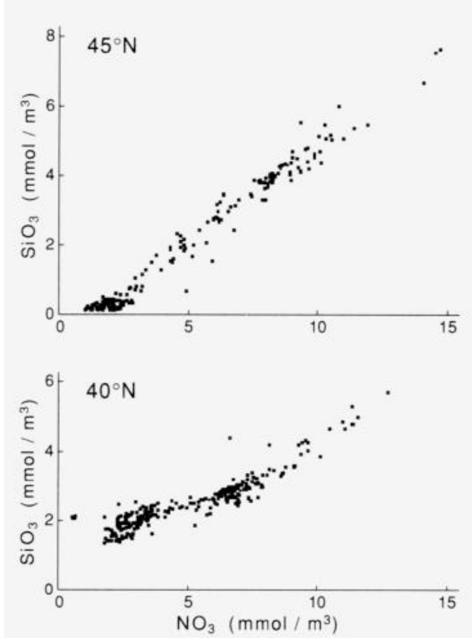


Figure 3. Regressions of silicate and nitrate concentrations in the mixed layer. At 40°N neither nutrient has yet become limiting for plant growth, while at 45°N the effect of silicate limitation, rather than the anticipated nitrate limitation, is clearly seen.

Our surprise at this critical finding perhaps stems from the fact that the majority of Atlantic spring-bloom studies in the past have been done at continental shelf locations, where the supply of silicates from shallow water dominates the nutrient balance. Maybe this result signals a basic difference in nutrient limitation between spring blooms in open oceans and those on continental shelves.

The scientific party of 18 DFO scientists on *Baffin* divided their work into nine different projects. In addition to applying the standard daily JGOFS protocols giving profiles of salinity, temperature, density, oxygen, irradiance, phytoplankton and bacterial biomass and growth rate, and zooplankton biomass, many process studies and special observations were also undertaken. The sediment trap studies were linked to computations of the proportion of total plant production based on regenerated nutrients and on nitrate supplied by turbulence and winter mixing. Surface coagulation associated with bubble formation in near-surface water, and the subsequent rapid growth of bacteria on the coagulated organic substrates, were investigated in relation to background bacterial respiration. Numerical, size-fractioned profiles of heterotrophic bacteria, of autotrophic pica- and nanoplankton, and of larger protists were obtained at each station by flow-cytometry or Coulter techniques. Bacterivory and herbivory by single-celled protistan plankton was measured at most stations and depths by grazing experiments using the dilution technique. Finally, the diel rhythms of feeding and the faecal pellet pigment and carbon production of the dominant copepod plankton were investigated in many experiments at most stations.

The experiences of all ships participating in the JGOFS Atlantic Pilot Study have been brought together in a subsequent drafting of the Scientific Plan for the main JGOFS studies in both the Atlantic and Pacific oceans during the coming decade. More nations have now indicated their intention to participate in these studies, and the coordination of all national JGOFS programs into a single series of international studies so that the whole will be greater than the sum of its parts is now proceeding. For this purpose, a permanent JGOFS office has been established with SCOR support at the Institüt für Meereskund in Kiel. A DFO biologist from the Northwest Atlantic Fisheries Centre (NWAFC) in St. John’s, Newfoundland, has been nominated as the JGOFS executive scientist and has taken charge of the coordination function at the Kiel office.

The scientific tasks to be undertaken by JGOFS during the 1990s are sufficiently complex that they are not reducible to a series of highly defined, critical measurements to be made over an agreed global network of stations. What will emerge from the study, however, are sufficient measurements of the processes controlling vertical carbon flux to enable us subsequently to parameterize the flux in region-specific algorithms linking ocean colour images to vertical carbon flux. From these will flow an ability to understand better the role of ocean biota in mediating climate change.

The Fisheries Ecology Program

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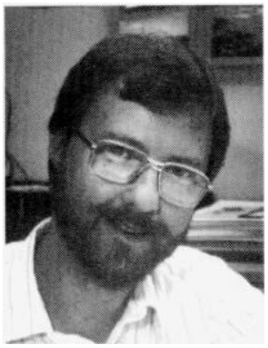
P. C. Smith



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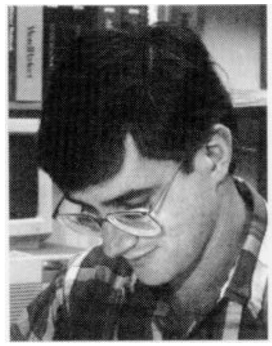
K. T. Frank



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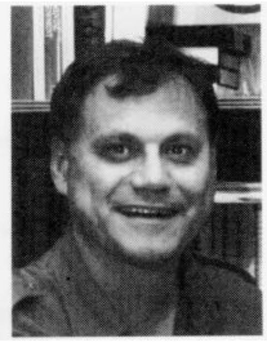

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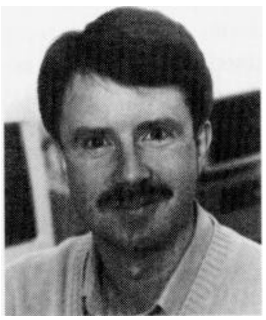


R. I. Perry

R. N. O'Boyle

The groundfish fishery off southwest Nova Scotia is the mainstay of the region's economy. The fishing industry employs approximately 12,000 people and generates approximately $100 million (landed value) annually. Haddock is one of the highest priced and most sought after of the groundfish species.

Haddock caught off southwest Nova Scotia are part of what is known as the Northwest Atlantic Fisheries Organization (NAFO) Division 4X haddock stock, a group of haddock separate from others in the northwest Atlantic. It is the job of fisheries managers to maximize long-term yield and economic return from a fish stock while protecting the stock from damage through overexploitation. Although the estimated long-term annual sustainable yield from the 4X haddock stock is 25,000 t, annual catches have only averaged about 20,000 t (Fig. 1; O'Boyle et *al.*, 1989). They peaked above 30,000 t once during the late 1960s and again in 1981; however, catches fell as low as 13,000 t in 1973 and, since the 1981 peak, have fallen to a low of 6,700 t in 1989.

The exploitation of haddock has been exceedingly high in recent years and estimates of fishing mortality are at least four times the target level. Symptomatic of this problem is the tendency for the landings to be dominated by fewer and fewer age groups each year (O'Boyle et *al.*, 1989). In 1982, five age groups each contributed over 10% to the total yield. In the following two years, only four age groups predominated, and in 1988 catches were dominated by only two age groups. Stock size is presently at an historic low.

Recruitment or yearclass strength (the

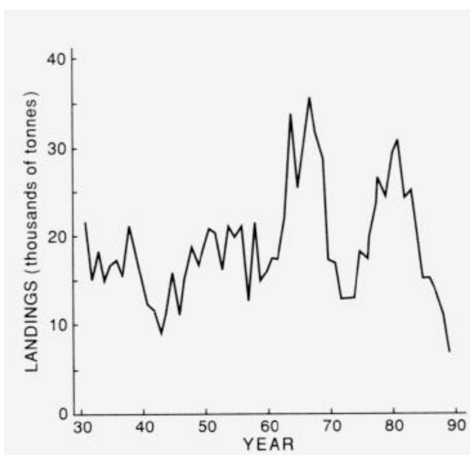


Figure 1. Long-term trends in 4X haddock landings.

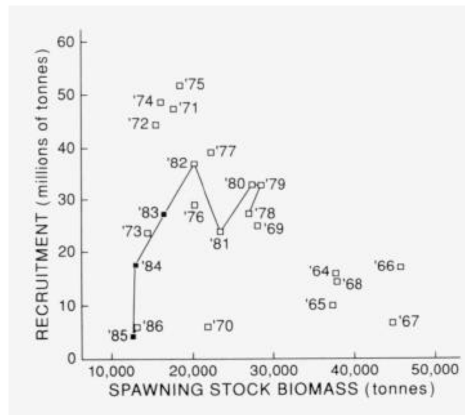
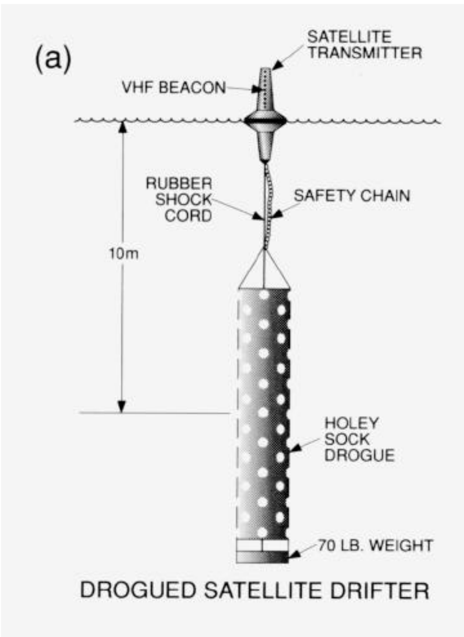


Figure 2. Relationship between spawning stock biomass and recruitment (at age 1) for the 4X haddock stock, 1964-86.

number of young that survive to age 1) in the 4X haddock stock has been highly variable over the years, changing by a factor of 12 since 1964 (Fig. 2; O'Boyle *et al.*, 1989). In relation to the long-term average of 24 million fish, recruitment was low in the late 1960s, strong during the mid-70s, and average in the early '80s. A string of poor yearclasses has occurred since 1984, and the 1985 recruitment was the lowest in 30 years. Unlike some other species, there does not appear to be a relationship between stock size and recruitment for this stock, which implies that factors other than or in addition to stock size (such as the environment) determine recruitment.

Because of the economic importance and the dynamic nature of the southwest Nova Scotia groundfish stocks, Scotia-Fundy scientists initiated a detailed study of the ecology of NAFO Division 4X haddock in the early 1980s. This multi-disciplinary study, called the Fisheries Ecology Program (FEP), involved researchers from a number of university and government laboratories, working in a wide variety of disciplines. As well as studying the biology of all life stages of haddock and the dynamics of the fishery, scientists examined the physical oceanography and primary and secondary trophic levels in the region.



To help improve the management of the 4X haddock stock, research focused on three main questions: to what extent is the stock self-contained; what factors are responsible for the highly variable recruitment; and what factors affect the distribution and growth rates of the stock? As a result of FEP, significant advances were made in our understanding of 4X haddock. This report summarizes some of the important findings of FEP and discusses how they may help to improve the management of the haddock fishery.

Physical environment

Many of the questions regarding the recruitment success of 4X haddock involve the role of ocean circulation in transporting the buoyant egg and larval stages. In particular, it was not known to what extent the permanent clockwise gyre on the western cap of Browns Bank (Smith, 1983) retains eggs and larvae in the face of tidal and wind-driven currents that tend to disperse them. To examine circulation and dispersion in the surface waters over the bank, a physical oceanographic field program, including an array of moored current meters, seasonal hydrographic surveys, and dispersion studies using satellite-tracked drifters, was conducted as part of FEP from April 1983 to May 1985. One of the major goals of these measurements was to define the time scales associated with the circulation and particle fluxes in this energetic regime, where variable currents are typically 3 to 10 times larger than the mean flow.

Surface-layer currents and particle dispersion were measured by tracking clusters of 5 to 6 buoys (Fig. 3a), which were centred at a depth of 10 m and initially deployed on scales ranging from 5 to 20 km. Simultaneous positions of all buoys were subsequently obtained with a relative accuracy of ±200 m by means of the ARGOS satellite system (Smith, 1989a). Drift tracks for selected deployments (Fig. 3b) reveal the tendency for particles in the

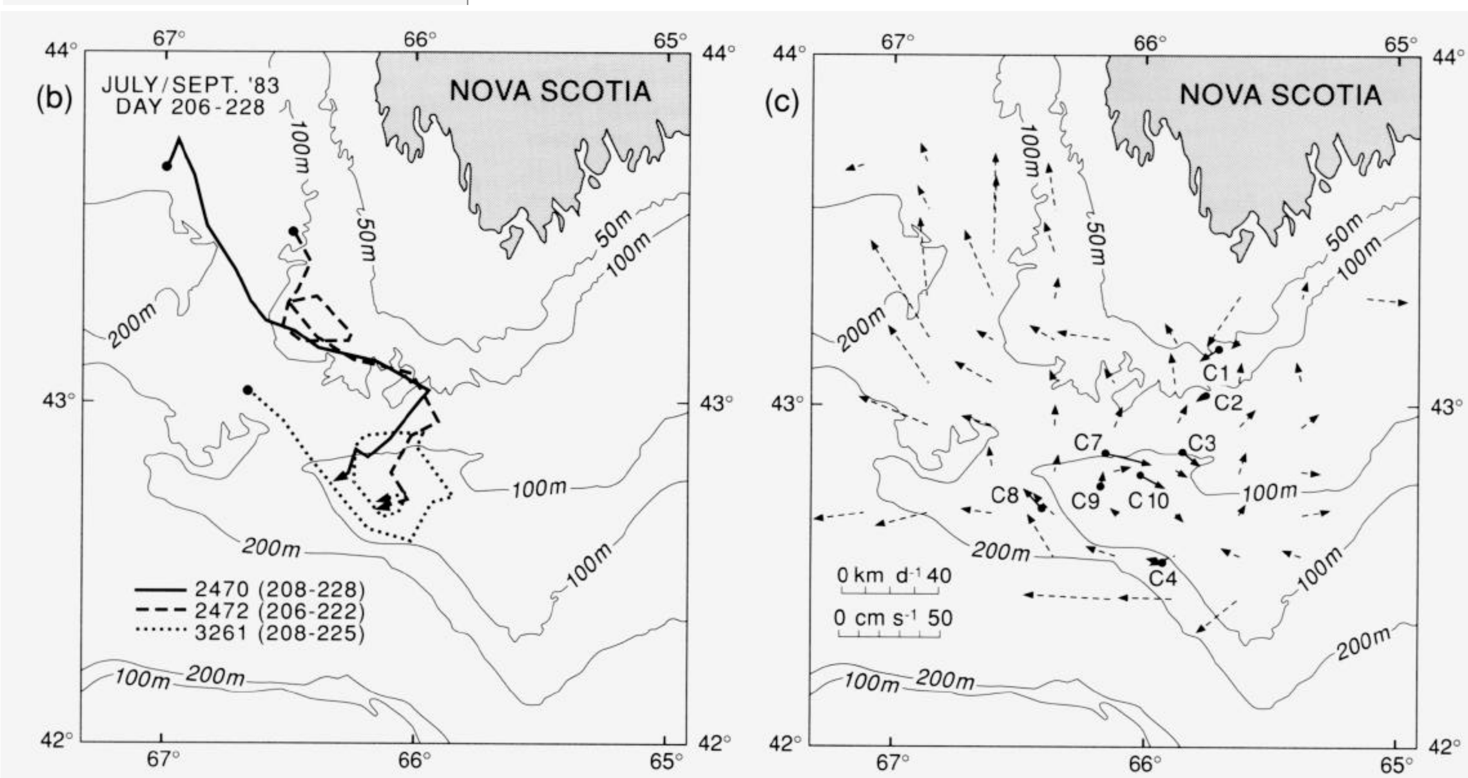


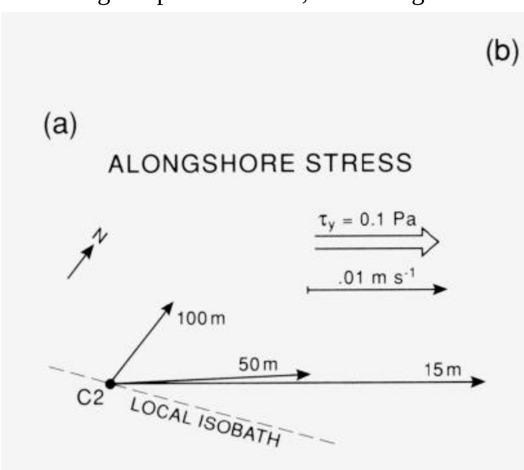
Figure 3. (a) Schematic diagram of a satellite-tracked drifter with a "holey sock" drogue centred at 10 m. (b) Smoothed drift tracksfor selected buoys during July and August 1983. A triangle and solid circle mark the beginning and end of each track, respectively. (c) Surface drift circulation (represented by the dashed arrows) off southwest Nova Scotia derived from 1/8° by 1/4° averages of all 10 m drift measurements in all seasons. The solid arrows represent mean near-surface currents from moored current meters, C1 through C10. (C5 and C6 are located off the map.)

surface layer to exit the bank from the northwestern flank as part of a "leaky gyre" circulation over the western cap. In some cases, a strong pulse of wind seemed to assist in "kicking" the drifters out of the gyre, but even in the absence of wind, escape to the north from the gyre over the western cap was consistently observed. A summary of the Lagrangian (particle drift) surface circulation, based on averages of all drift measurements in all seasons (Fig. 3c), reflects both the presence of the western cap gyre and the strong offbank flow along the northern flank of the bank. This picture contrasts sharply with that derived from the moored current meters. The moored measurements at 15 m also depict the gyral circulation but show no indication of the offbank flow to the north. The difference between these two results is related to the chaotic (turbulent) nature and strong spatial gradients of the background circulation. It clearly demonstrates that drift trajectories in this environment are not easily inferred from fixed-point measurements.

The most direct estimates of the residence time for drifting particles in the surface waters of the bank (Smith, 1989a) were derived from the statistics of repeated deployments. For a total of 10 deployments on the western cap during July through September 1983, the average residence time (i.e., the time spent on the bank or within 15 km of the 100 m depth contour) is 14 days. During the peak haddock spawning season (March to May), this figure was reduced somewhat by enhanced current variance caused by wind. These dispersion time scales are comparable to the biological time scales associated with the haddock egg stage (i.e., roughly 14 days from spawning to hatching), so physical transport off the bank could have a critical influence on survival. To date, attempts to simulate particle trajectories in the surface layer using a numerical model driven by wind and tides have not been entirely successful, though they have provided some keen insights into the physical processes which influence the drift (Page and Smith, 1989).

Interannual variability of the hydrographic conditions off southwest Nova Scotia may also exert a strong influence on the success of the 4X haddock recruitment through their influence on various biological factors, such as food availability, timing of the spawning cycle, and growth rates. As a measure of interannual variations, monthly mean data from moored current meters at two sites (C1 and C2; Fig. 3c) were analyzed. The longest of these time series (1978 to 1985 at C2) have been shown to be good indicators of the strength and timing of the annual pulse of low-salinity surface water from the Gulf of St. Lawrence (Smith, 1983) and are representative, at low frequencies, of records from both Browns Bank and the inshore zone off Cape Sable (Smith, 1989b). To complement the moored data, time series of other environmental variables (e.g., local wind, air temperature, and Gulf of St. Lawrence runoff) were also collected and analyzed. At C2, strong annual signals in temperature, salinity, and alongshore current were found to be related to seasonal transport induced by the May runoff peak in the Gulf of St. Lawrence, whereas the annual temperature cycle was largely controlled by local atmospheric forcing at the surface and by subsequent vertical diffusion downward through the water column.

The alongshore component of wind stress (defined as positive toward the east northeast) appear to influence the interannual variability in circulation and the properties of the water mass, although it does not do so on a seasonal basis. Significant correlations between the anomalies of alongshore stress and C2 currents about their annual cycles reveal an upwelling type of response to alongshore wind which is characterized by flow along depth contours in the upper part of the water column and by onshore flow near the bottom (Fig. 4a). These results are consistent with those



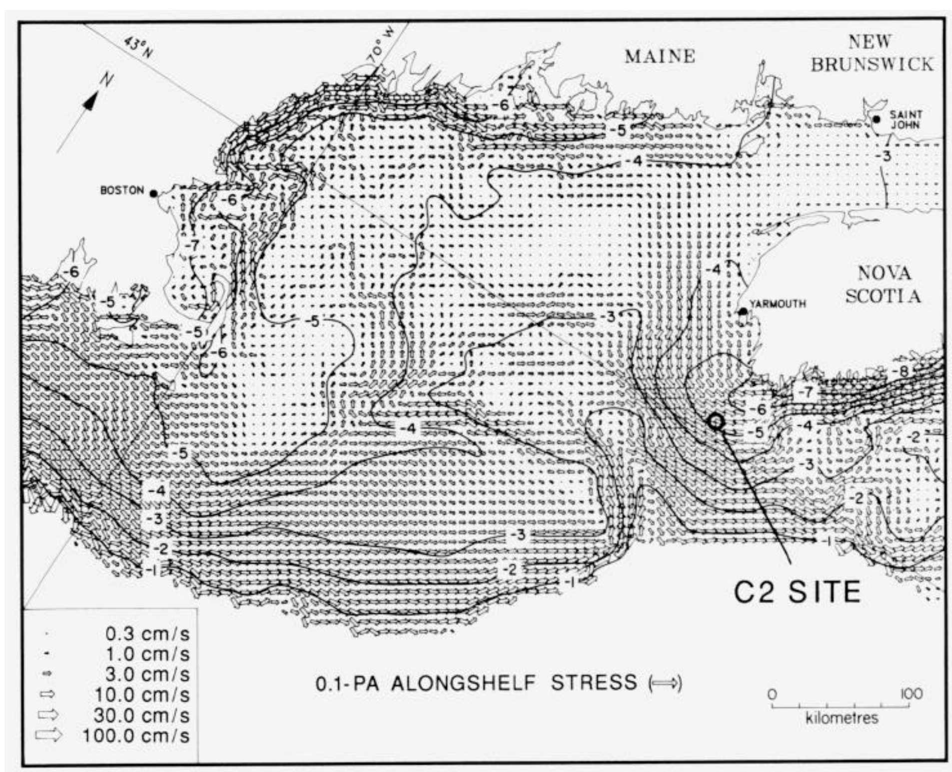


Figure 4. (a) Current response to a 0.1 Pa alongshore wind stress at Yarmouth, Nova Scotia, based on significant correlations between interannual anomalies from the annual cycles (Smith, 1989b). (b) Depth-averaged response of the circulation in the Guf of Maine to a 0.1 Pa alongshore wind stress, based on a linearized numerical model (Wright et al., 1986).

of a steady, wind-driven model (Fig. 4b), which indicates that the same alongshore wind drives an inflow of warm, salty offshore water into the Gulf of Maine through Northeast Channel, and then eastward around the western tip of Browns Bank and onto the Scotian Shelf. The circulation caused by positive alongshore stress anomalies in the fall of 1979 combined with the presence of a warm-core ring of the Gulf Stream offshore to produce the warmest, most saline conditions off southwest Nova Scotia during the seven-year C2 time series. Similarly, during the PEP field experiment, weakly positive alongshore stress anomalies in the period from March to May 1985 contrasted with strong negative anomalies in 1983 and 1984. The net result was reduced transport into the region from the Scotian Shelf and, consequently, higher temperatures and salinities during the haddock spawning season in 1985. In addition, differences in the timing of the wind stress anomalies in 1983 and 1984 produced significant interannual variations in the physical conditions of those years.

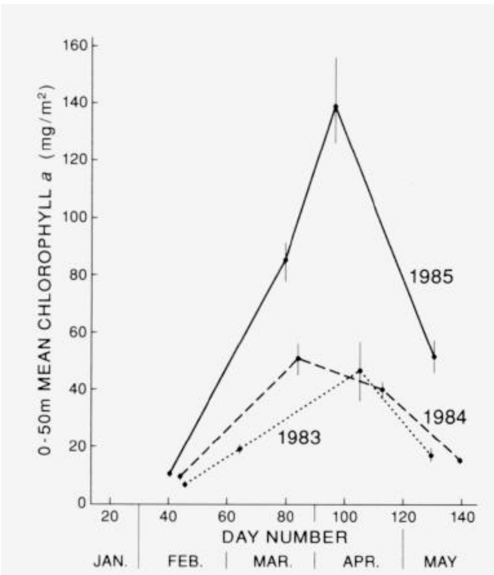


Figure 5. Survey of mean chlorophyll-a concentrations (integrated to 50 m). Error bars represent 1 standard deviation of the mean.

Primary and secondary trophic levels

Interannual variation in the timing and characteristics of the spring phytoplankton bloom were also investigated during FEP in the context of their potential importance to the survival of larval haddock. The anomalous winds in the spring of 1985 led to higher temperatures, higher salinities, and increased nutrients, particularly nitrate (Koslow *et al.*, 1989). That year was also characterized by greater solar radiation in late winter and spring than in 1983 or 1984. These factors, plus the somewhat lower zooplankton biomass in early spring, resulted in the chlorophyll biomass being higher during February to May 1985 than it was during the same period in any other year of the PEP field program from 1983 to 1985 (Fig. 5; Perry *et al., 1989).*

Survey observations indicated that the spring bloom had developed by the end of March or early April in all three years of the FEP field study. However, attempts to predict the conditions leading to the development of the bloom, based on survey data alone, were unsuccessful. In general, the initiation of a spring bloom is strongly influenced by the thickness of the surface mixed layer and the critical depth (the level at which primary production and respiration throughout the water column are in balance). When the critical depth exceeds the mixed layer, a bloom may occur. Survey observations of the critical depth and the surface mixed-layer depth indicated that the blooms should not have occurred until May, at least a month later than their actual development. To resolve this apparent paradox, the thickness of the surface mixed layer and the critical depth were modelled using oceanographic and meteorological data, including solar radiation, wind, tide, and buoyancy (freshwater) fluxes (Perry *et al.*, 1989). In agreement with observations, the model predicted that the bloom should have started about the same time each year. However, a number of transient stratification episodes were also predicted for early February and March in 1985. It appears that these events were of sufficient intensity and duration to have permitted short periods of increased phytoplankton production, thereby producing a higher overwinter biomass of phytoplankton in 1985 than in 1983 or 1984 (Fig. 6). When the major spring bloom occurred in 1985, this higher biomass of phytoplankton (plus the greater nutrient concentrations) led to the highest observed biomass of the series (Fig. 5).

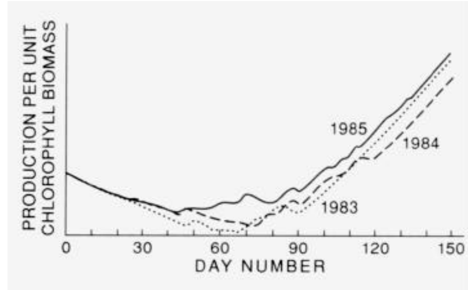


Figure 6. Calculated daily cumulative production per unit chlorophyll biomass, derived from the modelled light intensity throughout the surface mixed layer.

The results of the spring bloom model suggest that transient stratification events in winter and early spring are important to the initiation and characteristics of the spring bloom. This makes it difficult to identify a precise start for the bloom; for

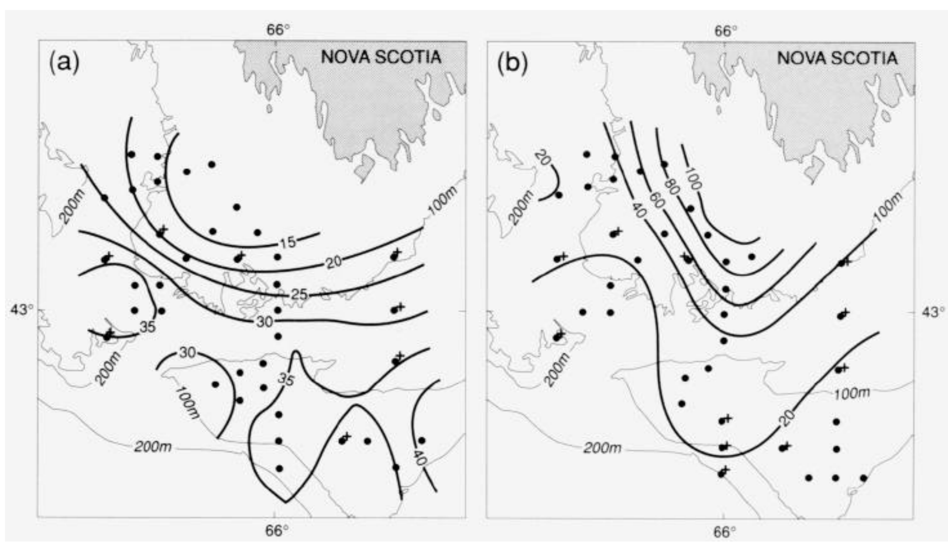


Figure 7. Distribution (mg dry wt/m³) of (a) large zooplankton and (b) microzooplankton, both from collections made off southwest Nova Scotia in May 1985.

example, does it begin with a series of short, transient events or with a single event at the end of March? It also demonstrates the intensity of short time-scale sampling that is required in order to observe such processes.

Both the model results and the survey observations indicate that the spring phytoplankton bloom was later in the shallow, well-mixed inshore waters than in offshore waters, due to strong tidal mixing which prevented stratification (Perry *et al.*, 1989). Chlorophyll biomass in spring was generally greatest in the deep offshore waters, due to stronger stratification (resulting from the lack of tidal influence on vertical mixing) and the deep nutrient-rich water available to resupply the surface layers during wind events. In contrast, these same offshore areas had the lowest chlorophyll concentrations in winter due to deeper mixed depths; the depth of mixing in shallow areas was limited by the bottom.

The biomass of the larger copepods and other zooplankton of a size suitable as prey for juvenile haddock was also highest in deep water and lowest in the inshore well-mixed region (Fig. 7a; Frank, 1988). In contrast, the spatial distribution of microzooplankton, the primary food of the early feeding stages of haddock larvae, was inversely related to the distribution of the larger zooplankton (Fig. 7b). Moreover, while the overall zooplankton biomass in late winter and early spring was lower in 1985 than in 1983 and 1984, the level reached by late spring was higher than at any time during 1983 or 1984. This late surge coincided with a marked decrease in chlorophyll, so that June was the only month when chlorophyll biomass was not highest in 1985.

It appears, therefore, that winter-early spring phytoplankton biomass off southwest Nova Scotia was enhanced in 1985 due to transient periods of stratification, and higher nutrient concentrations. This was followed by the highest zooplankton biomass of the study, during May and June 1985, that was apparently supported by the plentiful phytoplankton.

Early life history stages

Though Browns Bank has long been known as a spawning ground for haddock, very little was known of interannual differences in spawning time and location, or of the distribution and survival of the progeny. Moreover, the impacts of physical factors, which are known to contribute to large year-to-year variations in the survival (yearclass strength) of most fish stocks, had not been carefully evaluated for haddock off southwest Nova Scotia. This information, which is critical to the prediction of fish catches, was a primary target of FEP research.

Browns Bank is also a spawning ground for cod, a closely related fish species that spawns slightly earlier in the year than haddock. This proved to be of great advantage to FEP because it was possible to compare the two species and determine whether they responded in a similar manner to a given environmental factor.

FEP provided some surprising results with respect to the survival of both haddock and cod. It was not surprising that the physical environment influenced the distribution, growth, and mortality of both species; what was surprising was the manner in which it did so. The key proved to be the "leaky" gyre around Browns Bank (Smith, 1989a). The gyre was originally suspected of retaining eggs and larvae on the bank, a presumed region of enhanced production and prey availability. In fact, the highly dispersive nature of the gyre resulted in a drift-retention dichotomy for individual eggs and larvae, effectively splitting each of the early life-history stages into widely distributed inshore and offshore components (Fig. 8) (Campana *et al.*, 1989a; Hurley and Campana, 1989; Suthers and Frank, 1989). Growth (and presumably survival) differences within each of these areas were expected, given the observed variation in physical and biological factors (Fig. 7). In fact, during a May 1985 survey, the weight of young haddock larvae of a given length was nearly 40% less on the bank than off the bank. Furthermore, both the rate of egg development and the rate of larval growth were strongly influenced by temperature (Campana and Hurley, 1989; Page and Frank, 1989), which tended to be higher offshore than nearshore. In addition, stratified waters were generally associated with larvae in good condition (Frank and McRuer, 1989), resulting in regional disparities that apparently persisted into the pelagic juvenile stage (Suthers *et al.*, 1989). Stratification also influenced the vertical distribution of eggs and larvae, since the developing eggs tended to sink to a position of neutral buoyancy; the degree of aggregation was controlled by the stratification gradient (Frank *et al., 1989;* Page *et al.*, 1989). Eggs transported into low-density nearshore waters probably encountered the bottom and died (Frank *et al.*, 1989).

A second surprise resulting from analysis of FEP data concerned the effect of timing on growth and survival. Both haddock and cod exhibited interannual consistency in their respective spawning dates (Campana *et al.*, 1989b; Hurley and Campana, 1989), with no apparent dependence on temperature (Page and Frank, 1989). However, interannual temperature differences appear to have produced substantial differences in the timing of peak ichthyoplankton production, through temperature-mediated growth and survival. For instance, relatively cold waters in

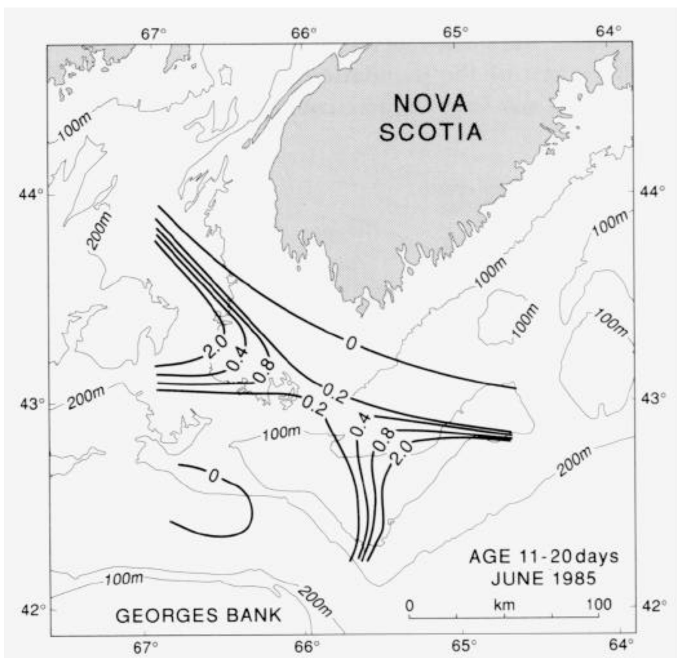


Figure 8. Contours of haddock larval abundance in June 1985 for larvae ages 11-20 days.

March and April of 1984 delayed the development and hatching of haddock eggs until late May, when rapid warming exposed the larvae to unusually warm conditions. This inconsistency in the characteristic physical conditions within a given year (or season) is not uncommon and reflects the high levels of intra-annual variability in the water masses off southwest Nova Scotia. It also indicates that designations of annual average temperatures as "cold" or "warm" are on too coarse a scale to be of value to early life-history studies.

Haddock larvae transform into juveniles when they assume the appearance of adult fish; this occurs roughly three months after hatching. For a period of time called the pelagic stage, they continue to feed upon zooplankton throughout the water column. Later they descend to the bottom and adopt a demersal way of life, feeding mainly on benthic invertebrates. Results from midwater and bottom trawl surveys in 1983 (Fig. 9) showed that the descent of juvenile haddock to the bottom occurred during a relatively short time, from July to August (Koeller *et al.*, 1986). Interannual differences in the date of descent and the widespread horizontal distribution of juvenile haddock have significant implications for the development of juvenile haddock surveys as recruitment estimators. They show that the timing and geographical extent of such a survey would be critical to its predictive success. For instance, too small a survey area could result in part of the population being missed, and too large an area could decrease the sampling rate below the optimum level. The improper timing of either a pelagic or a demersal trawl survey could result in biases due to differential sinking of different juvenile subpopulations from the pelagic to the demersal zone.

Before PEP began, the pelagic juvenile stage of haddock and cod development was probably the least understood. The information gained during the study will greatly increase the accuracy of surveys to predict recruitment.

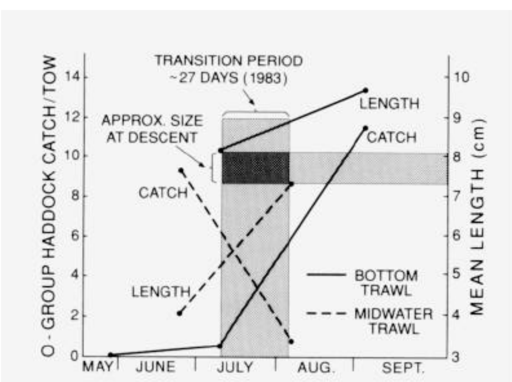


Figure 9. The timing of transition and the size of juvenile haddock at transition from pelagic to demersal habitat, as inferred from a series of midwater and bottom trawl surveys conducted in 1983 offsouthwestern Nova Scotia.

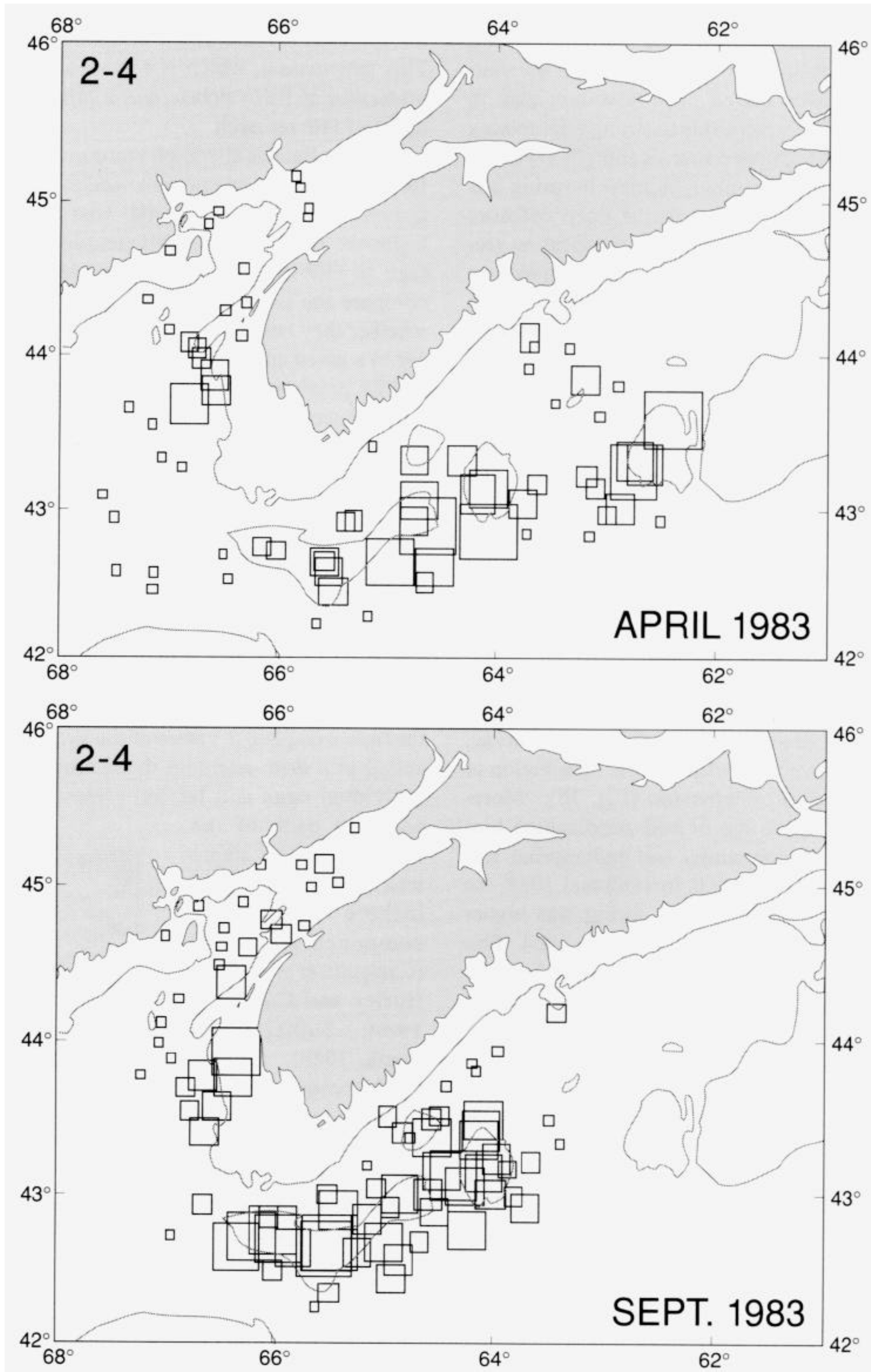


Figure 10. The distribution of haddock 2 to 4 years old, as inferred from bottom trawl survey catches in April and September 1983. The symbol area is proportional to abundance.

Adult biology

The distribution patterns of the early life history stages of haddock were believed to have an important effect later in life. So, during FEP the following two questions were asked: (1) is the duality in the spatial distributions observed in the early life history preserved in the later stages, and (2) do the growth differences observed during the larval period persist through time?

Seasonal groundfish surveys provided some answers to the first question. Young haddock segregated into inshore and offshore components during their first year of life and remained that way year round during most of their immature life (nearly 4 years) (Fig. 10). The older, fully mature age groups showed no evidence of segregation but did show a strong seasonal shift in distribution from the bank in late winter and early spring to the mouth of the Bay of Fundy during late spring and early summer. Spawning haddock showed a preference for a narrower and colder temperature range (1° to 5°C) than did fish of other stages of maturity and were observed most often in the area of a specific sand and gravel substrate (Waiwood and Buzeta, 1989). When combined, these physical features may serve to direct and reunite the stock at the time of spawning.

The answer to the second question was derived from data collected on the commercial fishery. The mean weight of fish at ages of 2 to 8 years was assessed by sampling catches of the dragger fleet fishing throughout NAFO Division 4X during January to March of 1983 to 1985. Without exception, the weight of fish in each of the six age groups was greater for fish caught in the mouth of the Bay of Fundy than for those caught in the offshore areas on the shelf (Fig. 11; O'Boyle, unpublished data). The magnitude of the weight difference diminished with age, averaging 46% for age 2 fish to 14% at age 8. The differences in weights between the two areas were also found when catch data from summer groundfish research surveys were examined. These results strongly suggest that the growth differences observed during the larval period persist well into later life. Could these growth differences also be related to the feeding conditions between the two areas? Haddock are known to be bottom feeders, and their diet is composed of a variety of invertebrate macrofauna. Interestingly, the production of benthic macrofauna production on Browns Bank averaged 64 g wet weight/m^2/year, versus 193 g wet weight/m^2/year in the Bay of Fundy (Wildish *et al.*, 1989). Thus, it is entirely possible that the three-fold-higher annual benthic productivity in the Bay of Fundy contributed to the growth differences seen among the older age groups of haddock. It is apparent that there are very real regional differences in growth potential for haddock in the 4X area and that the influence of variations in the physical environment during the reproductive period establish the distribution, growth, and yield characteristics of this stock.

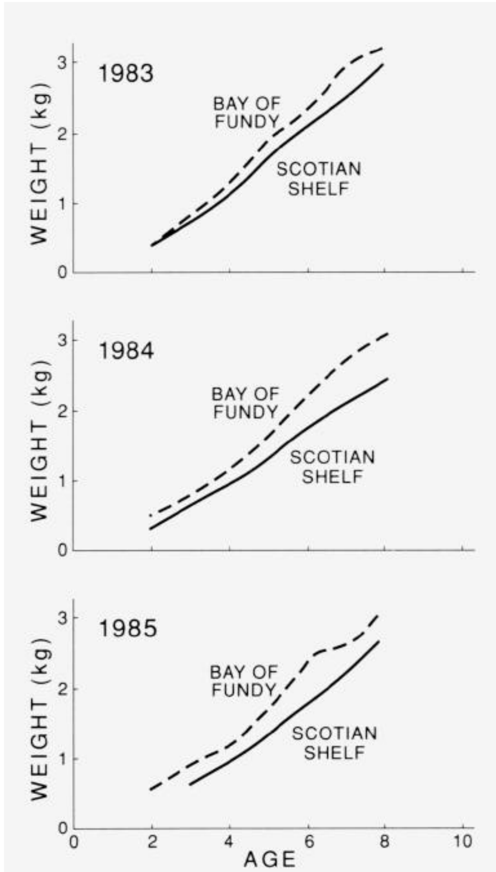


Figure 11. Weights at age for haddock caught offshore (solid line) and in the Bay of Fundy (broken line) in NAFO division 4X from 1983-85.

Synthesis

Synthesis of the FEP early life-history data in the form of survival curves highlights the massive fluctuations in haddock and cod abundances which occurred through the first year of life (Fig. 12; Campana *et al.*, 1989b). Although abundance declined by 5 to 7 orders of magnitude in the first 200 days of life in both species in each year, yearclass strengths at age 1 varied by less than a factor of 6 within each species. There was no apparent correlation between the abundance at either the egg or larval stage and the yearclass strength, suggesting that neither is likely to be a useful predictor of recruitment for these stocks. However, the abundance of both the pelagic and the demersal (not shown) juveniles was correlated with yearclass strength. Similar conclusions were reached with respect to mortality rates (Fig. 13); however, the mortality between the larval and juvenile stage was

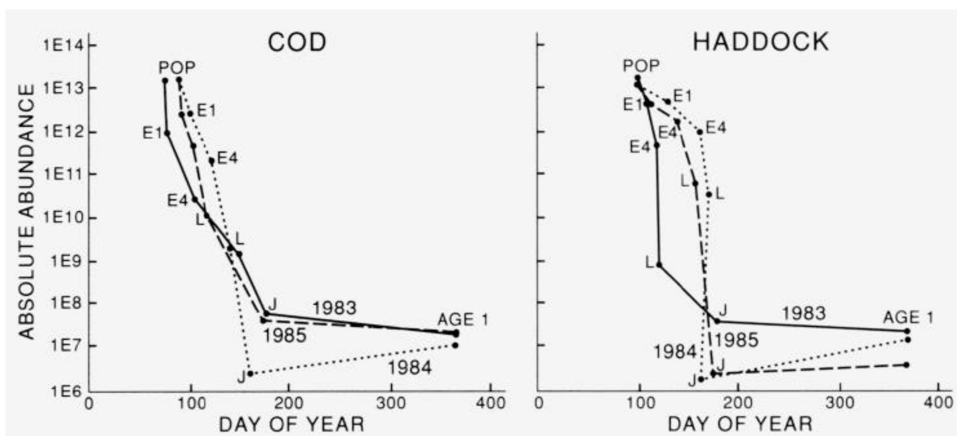


Figure 12. Survival curves for each of three cohorts (1983-85) of cod and haddock off southwest Nova Scotia. Estimates of absolute annual abundance (on a logarithmic scale) for each of the sampled life-history stages have been plotted against the corresponding mean weighted date of occurrence. POP = the population's egg production; E1 = early-stage eggs; E4 = late-stage eggs; L = larvae; J = pelagic juveniles; AGE 1 = end of first year of life, as derived from cohort analysis.

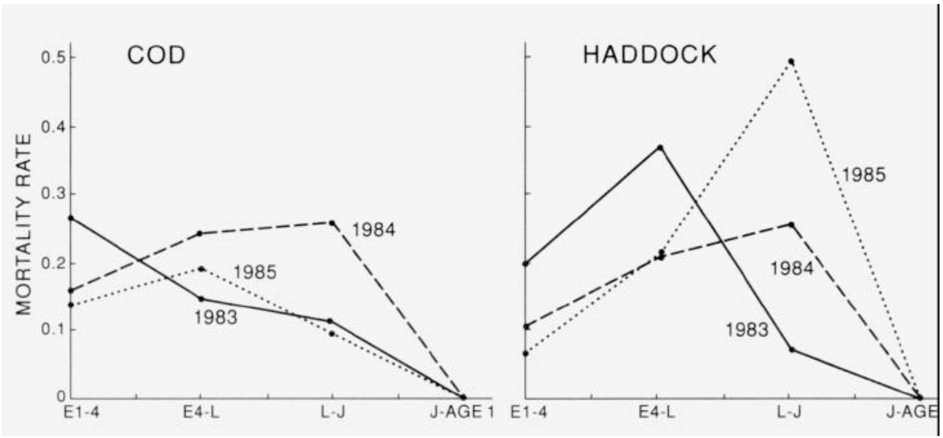


Figure 13. Daily mortality rates between life-history stages for each of three cohorts of cod and haddock (symbols as in figure 12). Time intervalsfor the mortality calculations were based on expected life-stage durations.

inversely correlated with yearclass strength. Unfortunately, the major sources of mortality could not be identified.

The identification of the juvenile stage as a proxy for yearclass strength may prove to be of predictive value to fisheries managers, assuming that a suitable survey methodology can be defined and implemented. The results of the juvenile surveys demonstrated the critical nature of timing and geographic coverage for such surveys.

A comparison of the relative yearclass strengths of haddock and cod demonstrated that exposure to the same large-scale effects in a given year need not result in similar recruitment success; despite similarities in spawning location and early-life distribution, the recruitment success of haddock and cod differed in 1984 and was totally divergent in 1985. Thus, the timing of local biological and physical events must have played an important role, beyond that of large-scale climatic events, in the recruitment success of these stocks.

While not all the factors controlling recruitment success in 4X haddock and cod were identified in FEP, significant advances were made in understanding these complex processes, and promising areas for further work were identified. Improvements in understanding the movements of mature and spawning fish, the location and timing of spawning, and the distribution of juveniles will have practical benefits to fisheries management. This information will assist in the definition of areas that can be closed to fishing during part of the year, thereby providing temporary protection for spawners and juveniles. Knowledge that there appear to be two areas of different production potential may influence thinking on the long-term harvesting strategies for this resource. Many facts concerning the adult biology of haddock and cod have already been incorporated into the annual assessment procedures, which form the basis for setting quotas (total allowable catches) for these stocks.

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Halifax Harbour: How the currents affect sediment distribution

G. B. J. Fader and B. Petrie

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The disciplines of marine science often carry out their research independently of one another, though in the same geographical region. The reason for this lies in the type of process that is under study. The physical oceanographer's interest is generally focused on waves, tides, and storm surges-phenomena that vary in time from seconds to days. On the other hand, by examining sediment distributions and characteristics, the marine geologist can address problems that occur over periods of time ranging from days to hundreds or thousands of years. Methods used in both subjects can differ as well. To measure currents and sea level, the physical oceanographer places self-recording instruments at a few specified locations for long periods of time. The one-time, remote-sensing acoustic survey conducted by a marine geologist from a ship is a powerful technique for characterizing regional sediment patterns, as the data collected represent an integration of all the processes that have affected the seabed. Both groups often bring samples back to the laboratory for further study: water, in the case of the oceanographer; sediment cores and bottom grabs for the geologist.

At first glance, these two disciplines seem to have little to offer one another; however, this is not the case. Both provide a different understanding of the same processes and can shed light on each other's problems. Average water circulation can lead to sediment transport and subsequent deposition in regions of very weak flow. High-energy currents generated by tides, storms, or waves can scour some areas of fine-grained sediments, leaving behind gravel and bedrock. Sedimentary deposits which reflect water movement over the years can tell physical oceanographers if their short-duration current-meter records are representative of long-term conditions. In the case of Halifax Harbour, information from the two fields of study was brought together to provide a better understanding of the currents and sediment distributions.

Halifax Harbour is an inlet whose mean circulation is known on a broad scale. Areas of strong, variable currents have been identified. Recently, the harbour has been the subject of thorough marine geological acoustic studies (Miller and Fader, 1989; Miller *et al.,* 1990), which have provided a regional understanding of the surficial and bedrock geology. In addition, sediment samples have been collected (Buckley and Hargrave, 1989) to provide "ground truth" for the acoustic data and to examine the geochemical changes the harbour has experienced since people started to use it for sewage disposal, shipping, and military activities.

Oceanographic and geological database

Our picture of the circulation of Halifax Harbour has come from current-meter measurements taken in Bedford Basin (1 site only), The Narrows (3 sites, with at least 3 instruments placed at different depths at each location), and the outer harbour (at 6 sites with 2 instruments each). The data were collected over periods ranging from a few weeks to about 7 months. Temperature and salinity measurements were made monthly for 2 years at 8 cross-sections of the harbour extending from the head to the mouth, with each cross-section having 3 to 6 measurement sites. These data have also contributed to our conception of the circulation.

Geological acoustic surveys covering the entire harbour use sidescan sonar systems to provide images of the ocean floor that resemble aerial photographs of land areas; the surveys also employ high-resolution seismic reflection systems which provide information on the sediment and bedrock below the seabed. From these data, the marine geologist can infer sediment type, sediment distribution, seabed morphology, structural style for the conditions of deposition, and information about seabed processes. In addition, seabed samples and cores which have been collected at about 250 sites throughout the harbour provide the confirmation and calibration of the acoustic data and contribute to the development of the sedimentary history model.

Average circulation of Halifax Harbour waters

Halifax Harbour is an estuary - i.e., a semi-enclosed body of water whose properties are influenced by freshwater runoff from the land. An idealized picture of the average circulation of the harbour waters is shown in figure 1. The near-surface waters tend to flow toward the ocean, becoming saltier as they move seaward through the harbour. The salt is supplied through mixing with waters from the Scotian Shelf, which enter the harbour in a layer which extends from the bottom to just below the outgoing near-surface flow. In turn, these shelf waters become less salty as they move into the harbour because of mixing with the shallower, fresher waters.

Salinity measurements in the harbour confirm this idealized picture of the average circulation and can be used with a model to derive horizontal current strengths and vertical mixing rates. In the surface layer, the weakest outflow, 0.2 cm s^{-1}, which is found in Bedford Basin, moves a parcel of water approximately 200 m in one day. The currents accelerate to their highest values, of about 5 cm s^{-1}, in The Narrows, slow to about 2 cm s^{-1} as the harbour widens in the downtown area, increase slightly at a narrowing off Sandwich Point, and, finally, slow to about 1 cm s^{-1} before flowing out onto the shelf. The picture is much the same in the lower layer, except it occurs in the opposite direction - i.e., inflow instead of outflow.

Current-meter data generally support this salinity-derived picture of the circulation in the harbour and, in at least one case, offer some additional detail. In The Narrows, the instruments recorded the strongest inflows near the bottom of the eastern (Dartmouth) side of the harbour.

The inferences for sediment distribution from this circulation pattern would be a general tendency for the finer sedimentary particles on the bottom to move toward the head of the harbour - i.e., toward Bedford Basin. Moreover, sewage particles, which enter the harbour waters in the surface layer, would initially be carried toward the shelf. However, as these particles sink, they would be caught up in the deeper inflow and would move back up the inlet. One might expect sewage-derived sediments to be confined largely to the inner harbour, The Narrows, and Bedford Basin, where the major sewage outfalls are located. There may be a tendency for greater sediment transport into the basin on the eastern side of the harbour because of the stronger currents found there.

Variable currents in the harbour

In the harbour, currents can change rapidly, with perhaps the most familiar variation being the tidal flows. Wind also can bring rapid, dramatic changes to the circulation by causing surface water to cross the harbour in perhaps an hour or by stirring up the bottom sediments through wave action. The strength of the varying currents as derived from all available current-meter data collected in the harbour is shown in figure 2, starting from the head of Bedford Basin out onto the shelf.

Variable currents are weakest in the basin, with an amplitude (peak strength of a variable current) of about 3.5 cm s^{-1}. Sediment deposition should occur in this low-energy area. The highest values, ranging from 15-35 cm s^{-1}, are found in The Narrows and are largely due to the tides. This is one area in the inner harbour that should be scoured of fine sediments. From Sandwich Point to the harbour mouth, the time-varying flows have amplitudes of 5-15 cm s^{-1}, with the lowest values occurring off Herring Cove. Although these areas have lower current variability than The Narrows, they are more exposed to ocean waves, which can affect sediment transport significantly. No data are available for the Northwest Arm or Eastern Passage, but one would expect them to have varying currents more like those in Bedford Basin than those in The Narrows.

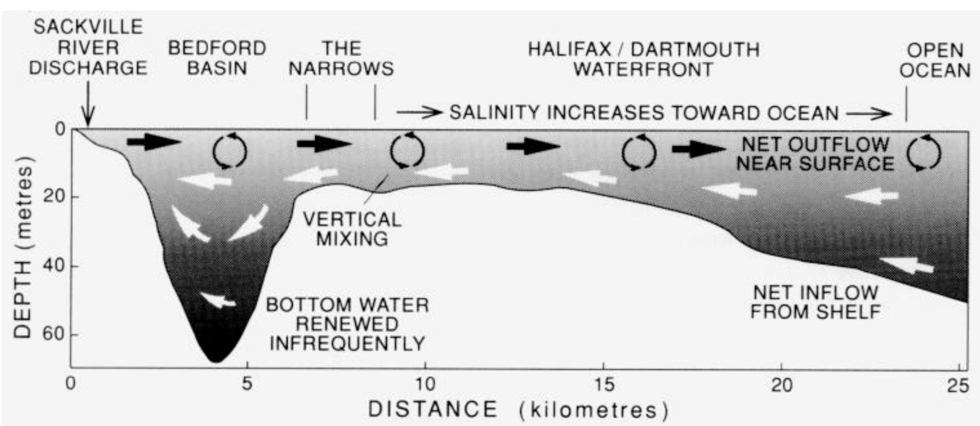

Figure 1. An idealized and simplified picture of the circulation in Halifax Harbour. Freshwater, represented by the Sackville River discharge, flows at and just below the surface from the head of Bedford Basin, through The Narrows and toward the open ocean.

Sediment history

The sediments on the seafloor of Halifax Harbour record not only the geological and natural history of the formation of the harbour, but also its most recent use as a depository of wastes since urban development. In addition, the sediments on the floor of the harbour have been modified by more direct disturbance. Dredges have scoured and deepened areas; docking facilities have been constructed and, in the process, shoreline areas have often been infilled; sand and gravel have been mined; dredge spoils, old ships, and large quantities of debris have been dumped; ships' anchors have been dragged; and discharge and intake water pipes have been constructed. All of these anthropogenic activities have interacted in a complex manner with the natural processes of sedimentation and sediment transport to produce the present characteristics of the harbour bottom. From a study of these characteristics, it is possible to determine the direction of sediment transport, the areas where sediments are being eroded or deposited, and areas of nondeposition. This information can be compared with the physical oceanographic data and used to fill in gaps where oceanographic measurements do not exist.

Sediment distribution

A map of the sediments in Halifax Harbour, as deduced from sidescan sonar, seismic reflection, and sample data, is presented in figure 3. Areas of coarse sedi-

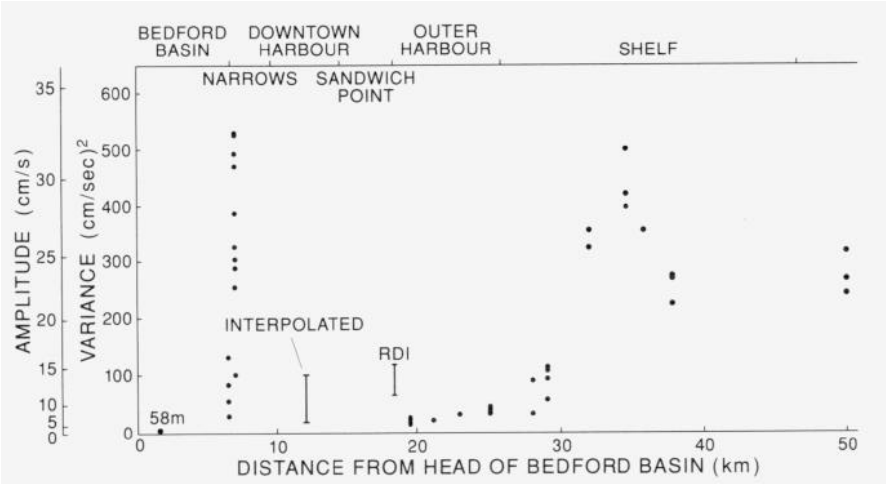

Figure 2. The variance of currents in the harbour and on the adjacent shelf, as derived from available current-meter data.

ments are widespread. North of McNabs Island, the most extensive area of coarse sediment is in The Narrows, corresponding to the region with the highest current variance. Another area of coarse sediment occurs approximately half way up the Northwest Arm adjacent to Flemming Park, where strong flows are not expected. The seabed consists of gravel with boulders and outcropping bedrock; fine-grained silts and clays are absent. As both of these areas occur at narrowing restrictions within the inlet, strong currents are interpreted as the responsible mechanism for preventing sediment accumulation. Other areas of the harbour are also devoid of fine-grained sediments: the entrance to Bedford Bay; Ives Knoll in the nearshore north of McNabs Island; the shallow coastal areas to a depth of 10 m; many bedrock shoals in the outer harbour; and vast expanses of the outer harbour to the southeast of McNabs Island. Wave action may account for the absence of sediment in the outer harbour and in the shallow coastal areas. In the inner harbour, to the north of McNabs Island, many small east-west trending ridges of coarse sediment protrude through the muddy seabed. Two unique boulder berms (linear ridges composed of boulders) ring Bedford Basin at a depth of 23 m. These were probably formed when the basin was a lake, approximately 6,000 years ago, and freezing of the waters of the lake concentrated the boulders as push ridges. The present distribution of coarse seabed areas thus has arisen from a combination of relict processes and modern conditions of high energy. The acoustic survey has allowed us to easily locate these high-energy areas; it would be virtually impossible to survey the harbour at this high resolution with current meters.

Much of the seabed in Bedford Basin and Bedford Bay is covered with muddy sediments. To the south of the hard gravel seabed of The Narrows, three large mud patches dominate the inner harbour. These extend seaward to the Maugher Beach area of McNabs Island. Mud also dominates the seabed of the Northwest Arm and Eastern Passage, again generally agreeing with the expectation of weak flow in the area. Beyond the Maugher Beach area, however, the character of the seabed changes dramatically and resembles that of the inner Scotian Shelf. The sediments are much coarser, bedrock crops out, and silt and clay particles are generally absent. In addition, sediment particles are well-sorted and are rounded to subrounded in shape, suggesting that they exist or were formed in a high-energy environment. Megaripples, which are bedforms in sand, and wave-formed gravel ripples are common. Bedrock outcrops in the many shoals, and the shallow seabed to the south of McNabs Island is characterized by vast ex-

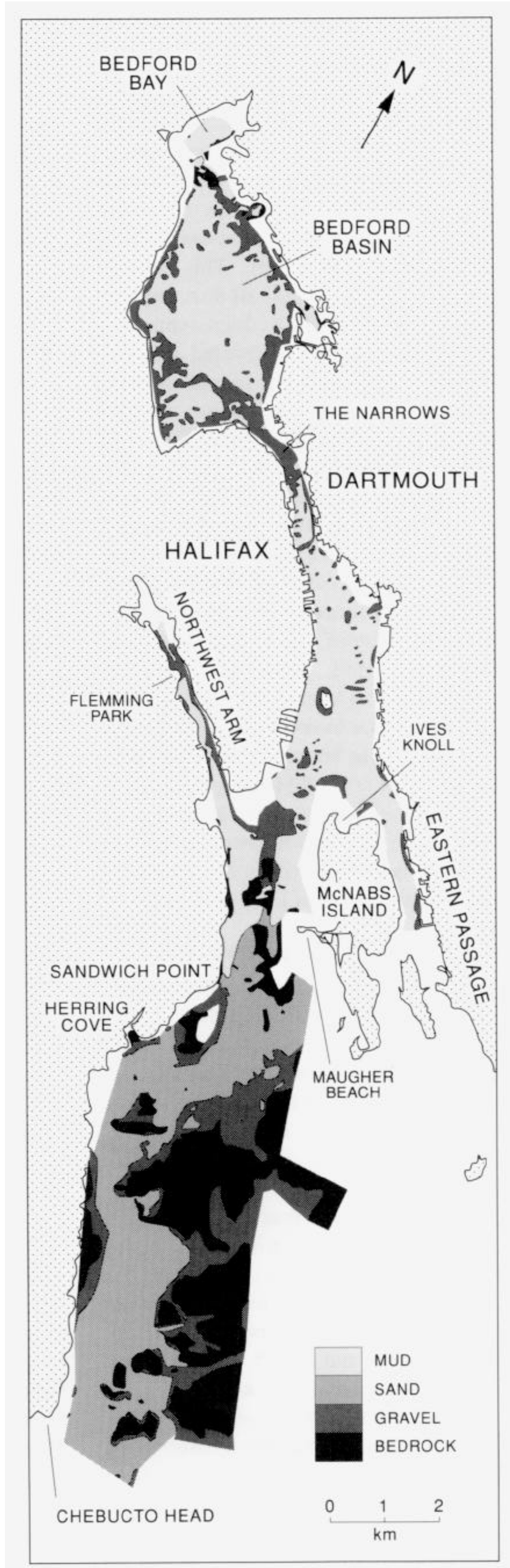

Figure 3. Map of the distribution of surficial sediments in Halifax Harbour.

panses of exposed bedrock, often strewn with boulders. This is an area where we expect surface wave action to have a significant effect. The outer harbour is dominated morphologically by a large, deep channel, which hugs the western side of the outer harbour from Sandwich Point to beyond Chebucto Head. In fact, this channel can be traced further seaward for over 30 km (King, 1970). This is interpreted as the channel of the ancient Sackville River that flowed across this area during times of glacially lowered sea level. The channel is floored by thin sands overlying glacial and estuarine muddy sediments in the subsurface. The first bedforms (megaripples) found outside the inner harbour occur in the deep 30-m channel off Sandwich Point. A major area of megaripples occurs to the south of Litchfield Shoal (south of Herring Cove) and continues further out the deep channel along the western side of the harbour to Chebucto Head. The area north of Litchfield Shoal is a similar sandy seabed, but megaripples have not developed. This suggests that the bottom currents have less energy in the area off Herring Cove. This area also has been identified as having the lowest current energy in the outer harbour and may be influenced by the sheltering topographic effects of Litchfield Shoal.

Anthropogenic characteristics

On the sidescan imagery collected from the inner harbour, including Bedford Basin, the most striking feature of the seabed is its anthropogenic imprint. This includes the presence of features such as anchor marks, dredge spoils, dredge marks, borrow pits, pockmarks (gas-escape craters), wrecks, cables, sewage banks, water intakes and discharges, propeller scours, and unidentified debris. In Bedford Basin, for example, over 80% of the muddy seabed is crisscrossed with anchor marks. These are linear-curvilinear scours, 1-2 m deep, which cut into and disturb the sediments. Overlying the anchor-marked surface are numerous deposits of dredge spoils. These are circular dumps of debris consisting of a wide variety of materials and grain sizes.

A geochemical characterization of the sediments (Buckley and Hargrave, 1989) has produced a series of maps depicting contaminant distributions throughout the harbour that appear related to the many outfalls presently located in the harbour. Some of these anthropogenic features and characteristics provide information that can be interpreted to provide an understanding of the movement of materials within the harbour or to identify areas of nondeposition and/or erosion. This, in turn, can be correlated with the physical oceanographic information to afford a better understanding of the dynamics of Halifax Harbour.

Sediment transport indicators

No direct measurement of sediment transport in Halifax Harbour has been undertaken. Such studies require the use of tracers together with subsequent monitoring programs and have been conducted only on Sable Island Bank on the Scotian Shelf (Amos and Knoll, 1987). However, many other characteristics of seabed sediments can be used as qualitative indicators. An interpretation of the orientation of features with respect to the responsible currents is one method. Features that can be used to deduce current patterns include the following: the distribution patterns of gravel, sand, silt, and clay; bedforms in sand and fine-grained gravel; scour features around seabed obstructions; the distribution of sewage banks; the distribution of geochemical anomalies relative to injection points; the presence of comet marks (obstacle-induced erosional scours); and the distribution of exposed bedrock.

The most easily identified indicators of sediment transport are the bedforms in the outer harbour. Here, the megaripples cover a broad area of the seabed overlying the bedrock channel of the ancient Sackville River. The megaripples have wavelengths of approximately 4 m and are less than 0.5 m in height. They are flow-transverse bedforms and are equally spread from crest to crest. Megaripples usually form at a mean flow velocity of between 40-60 cm s^{-1} (Amos and King, 1984). Some of the crests of the megaripples are broken into three-dimensional shapes. These features are normally generated under stronger turbulent flow. The shape of the three-dimensional megaripples indicates the transport of bottom sediment up the harbour to the north - i.e., in the direction of the mean current. In general, these megaripples are degraded, with less-clearly defined crests, suggesting that the event that formed them may have occurred several months to a year before. Browsing benthic communities often erode and destroy the crests of megaripples.

In many areas with slightly shallower water adjacent to the megaripples, large areas of ripples are present in gravel. These often flank the outcropping bedrock shoals between the bedrock and the megaripples. They are characterized by a wavelength of between 1 and 2 m and wave heights of less than 0.5 m. They do not indicate sediment transport but are formed in situ by oscillatory motion associated with waves. The areas of ripples in gravel and megaripples in the outer harbour indicate that fine-grained silt and clay sediments are not being deposited in these areas. Any sediments the size of silt and clay that were discharged there would be transported either further offshore to the inner Scotian Shelf or transported up the harbour to the north.

The sidescan sonograms from The Narrows were closely evaluated for sediment transport indicators, but none could be found. The presence of large boulders offers a setting appropriate for preserving comet marks and other scour features under strong flow. The seabed in The Narrows consists of coarse gravel and bedrock; silt and clay-sized sediments are rare. The conditions of flow are, however, high enough to prevent the deposition of most fine-grained sediments, indicating a bed-shear stress greater than 1 n m^{-2}. Currents exceeding this strength have been observed, some in fact reaching 90 cm sec^{-1} in The Narrows.

The distribution of geochemical anomalies in harbour sediments provides another indicator of sediment transport (Buckley and Hargrave, 1989). Many of these distributions suggest that material from the sewage discharges disperses and settles in a northerly direction along the shores of the harbour in agreement with the directions of mean flow. Anomalies of mercury suggest that material discharged from the Duffus Street and Tuft’s Cove areas are transported through The Narrows and deposited on the southeast side of Bedford Basin. In a similar fashion, the sewage outfalls at Pier A can be traced up the harbour to an area north of Georges Island.

The presence of anchor marks on the seabed of the harbour is an important benchmark that can also be used to assess the history of sedimentation and sediment transport. Large areas of Bedford Basin and the inner harbour are covered with crisscrossing patterns of anchor marks. Since they occur in most areas of the basin and in the major shipping channel of the harbour where anchoring is presently prohibited, they are interpreted as being relict - that is, formed at some time in the past with little subsequent modification or burial. Those in the basin are interpreted to have been made predominantly during the assembly of the World War II convoys, while those in the inner harbour may date back even further, to the founding of Halifax. Adjacent to the Halifax side of the harbour, recent sediment buries the old anchor-marked surface. Because the relief on fresh anchor marks is between 1 and 2 m, this indicates that more than 2 m of sediment has been deposited. The area of buried anchor marks projects up the harbour from the major sewer outlets in a fashion similar to that of the geochemical anomalies and suggests that the material is dispersed in a northerly direction as it settles to the seabed.

Conclusions

The oceanographic and geological data are in good agreement, indicating that bottom currents move up Halifax Harbour. The distribution of megaripples in the outer harbour suggests that currents are strongest to the south of Litchfield Shoal. This has prevented the deposition of fine-grained silt and clay sediments. The lack of bedforms in the sandy seabed north of Litchfield Shoal and adjacent to Herring Cove is consistent with the weak bottom flows measured by current meters. This local oceanographic anomaly may result from topographic sheltering by Litchfield Shoal. Coarse sediments in The Narrows are predicted from the oceanographic data, and the geological information confirms this prediction. In the Northwest Arm adjacent to Flemming Park, a similar lack of fine-grained sediments in a constricting channel suggests the presence of strong currents in an area where no current measurements have been made. The eastern part of the outer harbour is dominated by bedrock and gravel at the seabed. Many of the bedrock outcroppings in this area are flanked by rippled gravel deposits, which indicate that wave energy is reaching the seabed and that these are zones of high energy. Muddy sediments are confined to the area north of Maugher Beach. Their presence in the inner harbour, Eastern Passage, and the Northwest Arm reflects lower current velocities. Geochemical anomalies in the sediments, and sewage banks deposited over older anchor-marked sediments, indicate sediment transport up the harbour even in these areas of lower current velocities.

These examples help to illustrate how the disciplines of marine geology and oceanography complement each other. The physical oceanographer could not hope to measure the currents in as fine a spatial scale as the marine geologist surveys the sediments. From the sedimentary patterns, the oceanographer can infer the action of currents in regions broader than the measurement sites. On the other hand, by having direct measurements of flow, the geologist can begin to tackle the difficult questions regarding sediment resuspension and transport. In the absence of complete data sets, both types of information can be used to predict conditions that may exist in the marine environment.

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Sediment processes and habitat

K. Kranck

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The hydrosphere, like the atmosphere, is not a pure fluid but contains a solid particulate phase which, like the rain, snow, fog, and smog of the air, is a basic component of many of the most significant environmental processes. This marine suspended particulate matter is of varied origin and composition. Fine soil material from erosion of the land is transported to the sea by rivers. Organic production contributes living plankton cells and organic detritus. Many chemicals, including most of the man-made substances with which we contaminate our water environment, occur as particles or in association with particles.

Most particles spend a finite time in the sea and are sooner or later removed by various processes. The bottom of the ocean consists largely of muddy sediments resulting from the settling out of fine mineral grains. Phytoplankton and detritus also eventually settle or dissolve, either before or after consumption by higher organisms. In the long term, a virtual steady state exists between particle production and removal, but the short-term dynamic behaviour of particles is of concern to fisheries biology, coastal engineering, waste management, and most other branches of applied oceanography. At BIO, the Particle Dynamics Group of the Coastal Oceanography Division works on particle-related problems with the general goal of increasing understanding of the interaction between particles and other oceanographic factors. This work combines physics, biology, chemistry, and geology, and typifies the increasingly interdisciplinary nature of the whole field of oceanography.

Particulate matter is present in the sea because its downward movement, caused by gravity, is countered by upward mixing caused by turbulence generated by tides and currents. Consequently, most passively suspended particles are microscopic, and their most significant property is their settling rate, which is dependent largely on their size, density, and shape. Particles vary in size from bacteria and clay flakes less than a micrometre in diameter, to diatoms and sand grains with a diameter of several hundred micrometres. Their density varies from less than 1.01 g/cm^3 for living cells, to over 2.5 g/cm^3 for common silicate sediment grains. Shape also has a bearing on dynamic behaviour, and everything from perfect spheres to complicated delicate lace-like structures occurs. It is not unusual to find that the settling rate of particles in suspension varies by over six orders of magnitude at any one place and time, resulting in an enormous degree of complexity in the response of particles to dynamic forces in the sea. A further complication arises from the fact that particle size is not constant. In the presence of certain dissolved constituents, especially salt and organic matter, individual grains or cells are unstable and, on contact with one another, tend to stick together, or “flocculate”, to form larger, faster-settling units. Thus, in the sea and, to a lesser extent, in freshwater, suspended particulate matter forms aggregates, or “flocs”. These flocs are very fragile and, although they have been seen and photographed underwater, they fall apart when they are sampled or subjected to standard particle-analysis procedures.

At the present time, our inability to determine the distribution of size and the settling rate of particles in the ocean is a major hindrance to understanding particle-related processes. Evidence for this is the fact that, within BIO, several groups are experimenting with different systems for measuring particle size in situ. The Coastal Oceanography Division is using a Benthos plankton camera (Figs. 1 and 2) for the purpose, and within the Atlantic Geoscience Centre a stereographic camera system has been designed; both groups are using an automatic digital image-analysis system to derive particle distributions from the photographs they take. Scientists in the Metrology Division have long been using electronic sensing systems to count zooplankton and are now ready to apply their techniques to smaller particles. It is hoped that one of the approaches being pursued at BIO, or two or more in collaboration, will succeed in reaching the coveted goal of measuring *in situ* particle-size distributions over the whole range of particle sizes.

The one property of a suspension which scientists can measure accurately is the size of individual inorganic sediment grains. During transport in a suspension, the *in situ* size may change due to flocculation, but the size of individual mineral fragments is relatively stable. The disaggregated inorganic grain-size distribution of a sediment is an indicator of its source and history. In order to develop methods for more accurately interpreting the characteristics of sediment grain size,

Figure 1. The deployment of‘ the Benthos plankton camera at the confluence of the Mackenzie and Red rivers, Northwest Territories, to obtain in situ *photographs of suspended particulate matter flushing through the open image area between the strobe light and the camera package.*

Figure 2. The camera being lowered into a fish pond in Bangladesh.

studies are currently using precision size-analysis techniques developed by the Particle Dynamics Laboratory and based on the Coulter counter. Comparison of the size spectra of the grains in suspension with the size spectra of the sediment on the sea bottom in different marine environments has helped to unravel the evidence contained in these records of present and past environmental conditions. It has been established that, at the coarse end of the size distribution, an abrupt falloff in grain sizes usually occurs, and the size of this maximum is a function of the turbulence levels keeping the particles in suspension. The effects of flocculation on grain-size distributions have been investigated in the laboratory. Unsorted sediment suspensions with size distributions similar to those of most rivers and estuaries - that is, with about the same volume of material in all the size classes - were placed in beakers and allowed to settle. Monitoring how size distribution changed with time showed that when salt was added to a suspension to cause flocculation, all grain sizes settled at the same rate, whereas when flocculation was prevented, only the largest grains settled during a given period of time (Figs. 3a and b). This indicates that flocculation forms aggregates composed of a representative fraction of all the sizes and types of particulates found in the parent suspension. As most parent materials are unsorted, this provides criteria for estimating whether bottom sediment was deposited as single grains or as part of flocs. Using the grain-floe model based on this concept, most fine-grained bottom sediments can be shown to consist of two fractions: a coarser fraction with a narrow range of grain sizes, and a finer fraction composed of all grain sizes (Fig. 3c).

Studies indicate that most oceanic bottom material has settled as part of flocs. Without flocculation, most muds would not form, and fine particles would remain suspended in the sea for a very long time or until a sufficiently thick slurry formed to dampen the turbulence which normally prevents clay grains from settling.

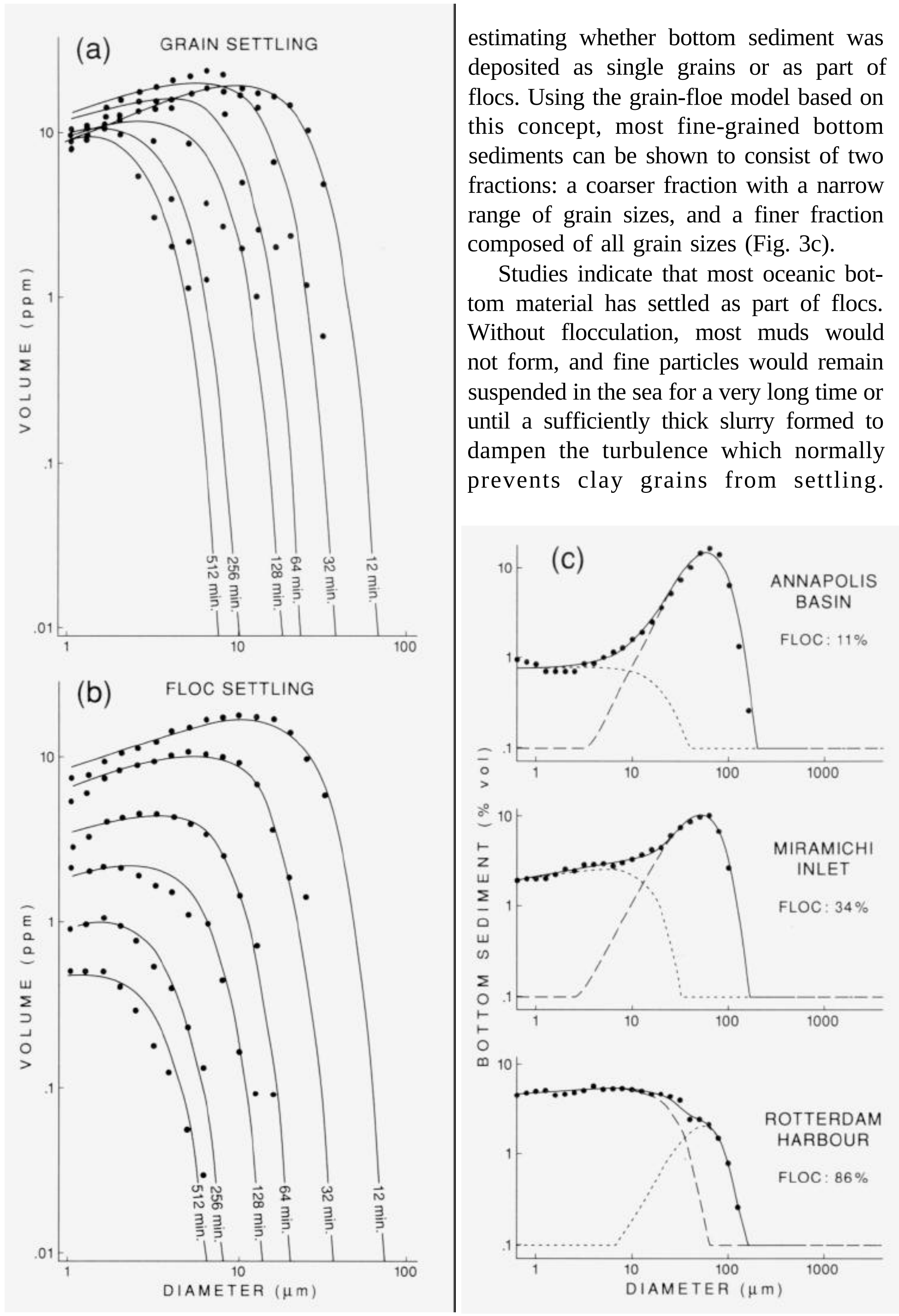

Figure 3. Grain-size analysis plotted as log-log plotted frequency distribution spectra. The dots show the results from the Coulter counter, and the lines show the fit of floc-grain model equations to the data. Parts (a) and (b) show the results of the laboratory experiment testing differences in the effects of single grains and floc settling on the grain-size distribution of a suspension. Identical sediment suspensions were settled in distilled water (a) and sea water (b) and the sediment size distribution was measured (disaggregated) after increasing time intervals. In the unflocculated suspension (a), concentrations decreased principally in the largest single-grain size classes, whereas in the flocculated suspension (b), the concentration decreased in all size classes as the small grains formed faster-settling flocs. (c) Bottom-sediment grain-size spectra from three estuaries illustrating the dual origin of fine-grained sediment. The broken line indicates sediment deposited as single grains; the dotted line indicates sediment deposited as flocs; the solid line indicates the total.

Flocculation also rids the marine environment of detritus, such as the products of organic production. Without its cleansing action, decreased transparency would greatly reduce sunlight penetration, and the present levels of primary production in the sea would be impossible. Lakes in the Arctic filled with glacial meltwater, which is low in salt and organic matter, are examples of a sedimentary environment where no flocculation occurs. Field studies conducted by the Particle Dynamics Group near Pond Inlet on Baffin Island have documented the abundance of a very fine unflocculated mineral-grain suspension in these lakes. The most visible manifestation of a lack of flocculation is the flashy "roiling" pattern that occurs as a result of light reflecting off single clay flakes oriented parallel to turbulence stream lines, a phenomenon seen on the surface of certain freshwater bodies but never in the sea (Fig. 4). For further comparison between flocculating and nonflocculating conditions, samples of loess, the fine-grained windblown sediment covering much of the mid-latitude land areas, have been obtained from around the world by direct sampling and in exchange for analyses. These samples have been found to be missing the finest-grained fraction, confirming the unflocculated nature of the parent suspensions (near-surface air currents of the late Pleistocene) and placing an upper limit on the grain size of aerosols.

In addition to the work on glacial lakes and loess, the Particle Dynamics Group has undertaken other studies in environments where some special combination of environmental conditions allows easier investigation of a particular effect than is possible in the marine environment. Often these studies are carried out in collaboration with scientists engaged in research of a more conventional applied nature. For example, when the extreme shifts in current energy characteristic of tidal estuaries were found to hamper studies of sediment transport, an environment with more uniform current conditions was needed and a study of riverine-suspended sediment was commenced. This has included studies of sedimentation in Bangladesh and the Canadian Arctic, both of which are being carried out in cooperation with major river-management studies of other institutes (Fig. 1). Similarly, sediment from deserts, tropical laterites, and glacial tills have helped to characterize the size of newly formed weathering products, unmodified by any fluid sorting. Studies of environments with very high concentrations of suspended particulate matter have been carried out in estuaries where repeated dredging has formed an easily resuspended low-density, near-bottom, fluid-mud layer. These are environments where floc formation is at a maximum. Both general experience and the results from studies of fluid mud undertaken in Rotterdam Harbour and San Francisco Bay have been applied to Miramichi Inlet, New Brunswick, where, as in the other two harbours, an artificially deepened channel collects dredge spoils from previous dredging and dumping activity. Repeated sampling of the bottom near the principal dumpsite in Miramichi Inlet (Fig. 5) shows the migration of spoils along the bottom and the progressive formation of dredging-derived, low-density fluid mud, a sediment type first identified in Holland.

One of the prime objectives of the particle studies is a better understanding of marine ecological habitats. During phytoplankton blooms, very high concentrations of single cells and chains occur

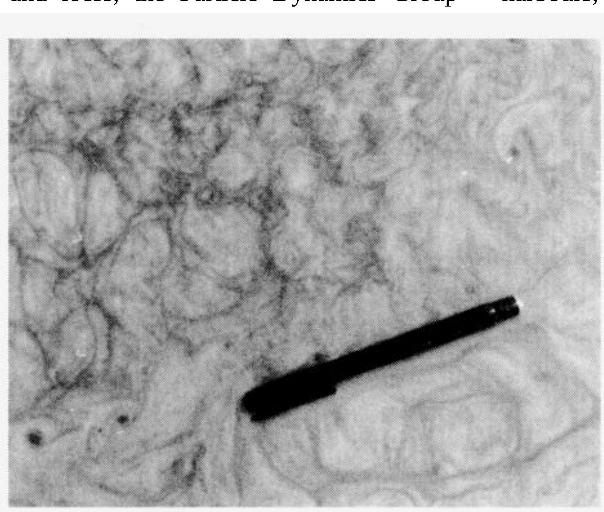

Figure 4. The roiling pattern caused by light reflecting off unflocculated suspended sediment in the Mackenzie River at Fort Simpson. The length of the floating pen (provided to show scale) is 14 cm.

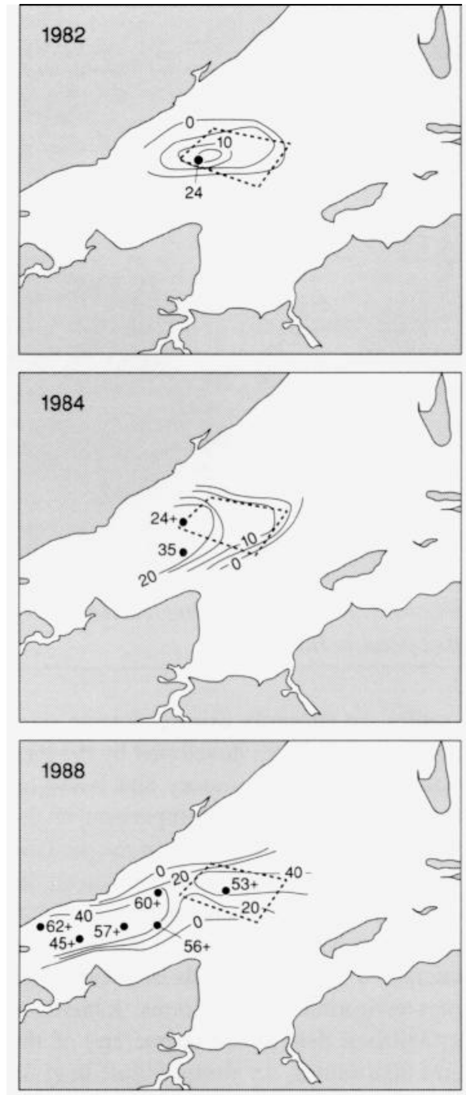

Figure 5. The thickness in centimetres of dredging-related sediment during three different years in Miramichi Inlet, New Brunswick. The contour gives the thickness of the deposit, and the outlined area shows the designated dumpsite for dredge spoils.

in the water column. This is in apparent contradiction to the observation that all high-concentration seawater suspensions flocculate readily. A Benthos plankton camera which photographs suspended particulate matter *in situ* was used to study a diatom bloom in Bedford Basin. Photographs collected over 10 days showed that, although the diatoms in fact started as single units, after some time, like other particles, they began to aggregate into flocs (Fig. 6). This caused them to settle to the bottom through the thermocline, which up to then they had not penetrated. Only by photographing the diatoms *in situ* could

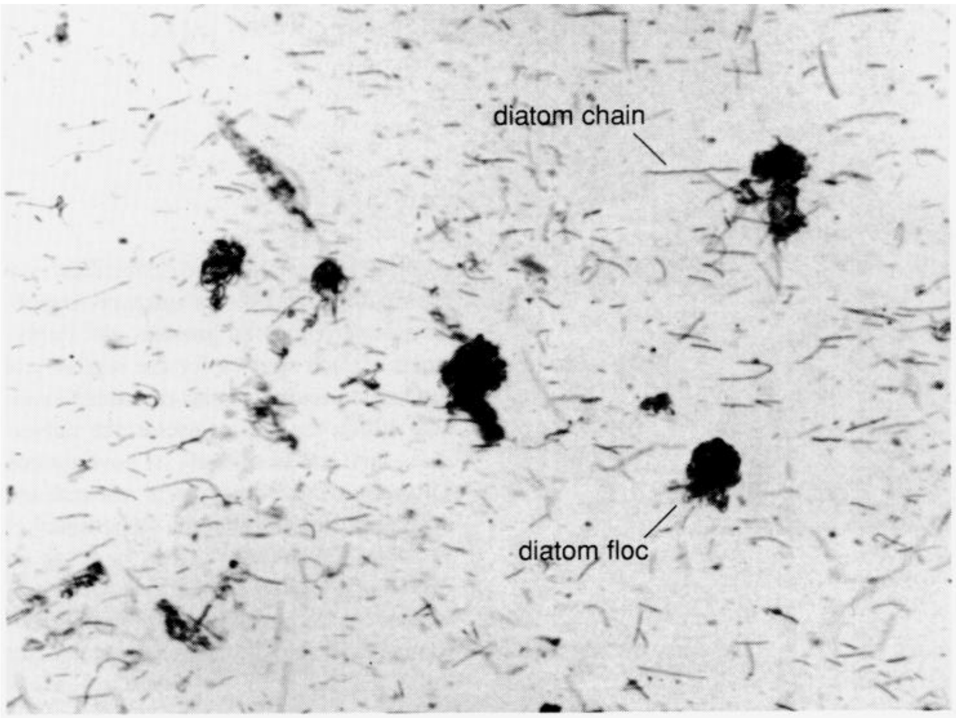

Figure 6. A flocculating diatom bloom photographed with the Benthos plankton camera and magnified approximately 4.5 times. The camera takes photographs in situ *of a 4-cm-thick segment of water. The needle-like particles are individual diatom chains (mainly* Chaetoceros), *and the larger clumps are diatoms which haveflocculated to form irregular aggregates of various sizes.*

the diatom flocs, which fall apart when sampled, be detected. Flocculation is also relevant to the understanding of benthic habitats, where bottom fauna feed on organic-rich flocculated particles transported along the bottom. The flocculation of all the components in a suspension results in the formation of flocs in which inorganic grains act as ballast to keep lighter nutrient-rich organic matter concentrated near the bottom. This is obviously a factor in the culturing of mussels, where flocculation controls the food that is available to these animals which feed selectively on particles of a certain size.

The Particle Dynamics Group's plans for further research include a study comparing the size distribution of living and nonliving particles. Phytoplankton are subject to the same physical constraints as other suspended particles, but living phytoplankters also have properties which counteract gravitational settling, such as flagella for locomotion and the ability to regulate their density. Mineral grains, however, are relatively inert and do not change their physical properties readily. Flocculation can increase the settling rate of smaller grains but does not seem to affect the maximum settling rate of the largest grains in a suspension. The hypothesis that similarities in the size spectra of living particles and mineral grains indicate aspects of phytoplankton which can be attributed to purely physical factors will be tested and used to study phytoplankton variability. This work will be carried out in conjunction with studies of the effects of aquaculture sites on the marine environment of small bays and estuaries in the Maritime Provinces.

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Science and aquaculture: A matter of demand and supply

R. H. Cook and R. E. Lavoie

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Aquaculture has been practiced for a long time in Canada. The first hatchery-raised trout was produced near Quebec City in 1857, and Atlantic salmon followed in 1858 (Nettle, 1857; Dunfield, 1985). Oyster culture started officially in 1865 when the Government of Prince Edward Island passed a statute providing for the leasing of specific areas for the purpose of growing oysters (Mathieson, 1912; Lavoie, 1989). These endeavours were based on the results of pioneer research aimed at gaining a measure of control over the reproduction and production of aquatic species for commercial and recreational purposes.

Successful modem aquaculturists know their cultured species well and study candidates for introduction carefully. Knowledge of the life history and of the biological and habitat requirements of target species is a prerequisite for site selection and for establishing business plans. Growers must be aware of predators and potential disease problems in order to prevent their occurrence through careful husbandry, and they must plan for damage control. They must also know the quality standards and the demands of the markets where they intend to sell their products. Assembling and developing such knowledge is often beyond the capacity of prospective growers.

This is where science comes into play. Scientists anticipate the demand for technical information, exploit domestic and foreign sources, identify gaps in the relevant knowledge, and carry out the necessary research. The final product is information needed by producers, private investors, economic development agencies, and the regulatory branches of provincial and federal governments.

The aquaculture industry is developing rapidly in the Scotia-Fundy Region in both its finfish and shellfish components. Commercial grow-out areas, as well as hatcheries, research centres, and experimental sites, are scattered throughout the region, except in the upper reaches of the Bay of Fundy (Fig. 1).

Research on each species varies according to the anticipated demand for new information, requests for solutions to problems experienced by growers, the importance of each species for the region, and the human and financial resources available within the private sector, the universities, and the two levels of government. This article describes current research and development work that the Department of Fisheries and Oceans (DFO) is doing on finfish and molluscan shellfish culture, as well as the impact of aquaculture on environments. It also presents a perspective for the future.

Finfish aquaculture

The commercial culture of finfish in the Maritimes is a relatively recent activity and is based exclusively on the grow-out of Atlantic salmon *(Salmo salar)* and rainbow trout *(Oncorhynchus mykiss)* in sea cages. This activity has highlighted the benefits of aquaculture and its potential as a vibrant socioeconomic force. But success did not come easily. Several experiments conducted in the ’60s in Cape Breton, near Peggy’s Cove, Nova Scotia,

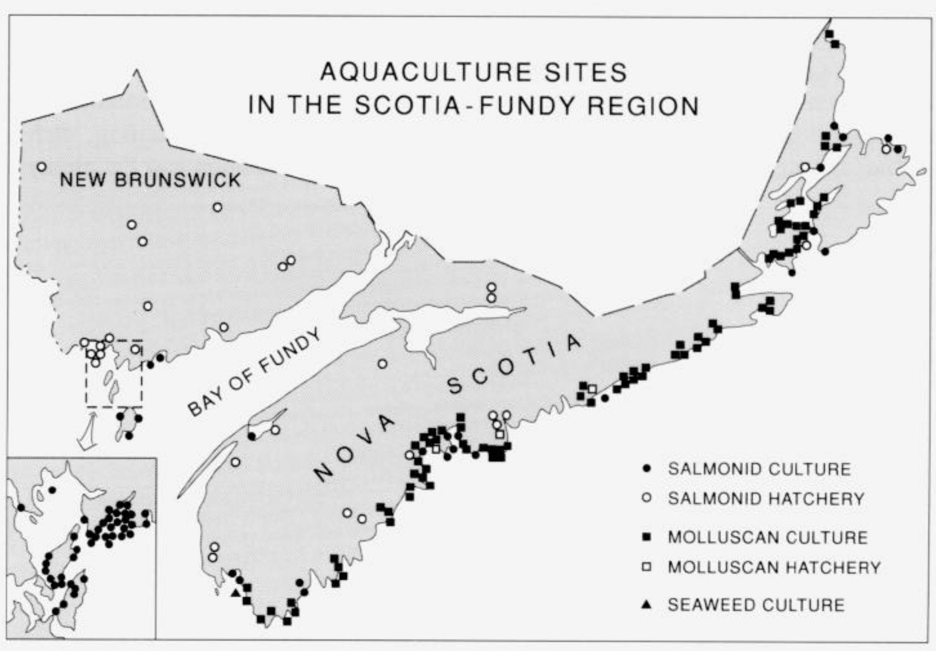

Figure I. Aquaculture sites in the Scotia-Fundy Region.

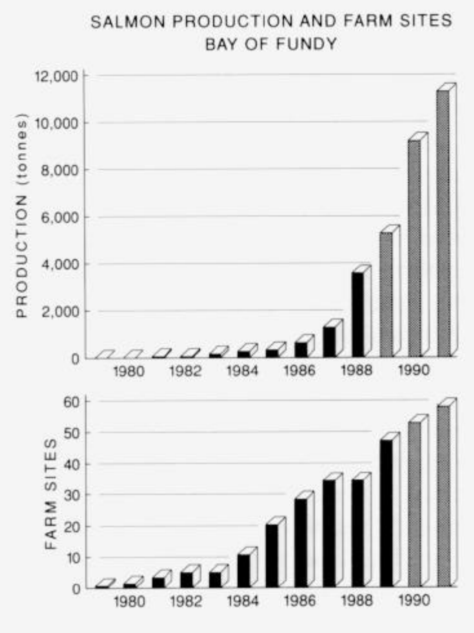

Figure 2. Historic trends in commercial salmon production and the number of farm sites in the Bay of Fundy.

and at St. Andrews, New Brunswick, proved unsuccessful due to lethal winter water temperatures. In addition, the collapse of a pioneer aquaculture company called Seapool, at Lake Charlotte, Nova Scotia, in the early ’70s discouraged investment in the industry for over a decade. In the late ’70s Dr. Ame Sutterlin, a scientist at the St. Andrews Biological Station who had spent a year in Norway studying that country’s aquaculture industry, started a pilot project in the Bay of Fundy and demonstrated the feasibility of Atlantic salmon culture at sites selected to avoid the lethal temperatures (Sutterlin *et al.,* 1981; Cook, 1988). The statistics from the resultant cultivated salmon fishery in the Bay of Fundy are impressive (Figs. 2 and 3).

Science has played a pivotal role in the development of this new industry. Investment in scientific studies on salmon physiology at the St. Andrews Biological Station and on fish disease and nutrition at the Halifax Fisheries Research Laboratory has provided comprehensive knowledge for immediate application. Promulgation of the Fish Health Protection Regulations (Anon, 1977) and the establishment in 1976 of DFO’s Fish Health Unit in Halifax to provide certification and diagnostic services were also fundamental to the industry’s success. Moreover, with the long history of Atlantic salmon enhancement programs in the Maritimes and the supporting network of fish culture stations, we were able to provide high-quality seedstock to the industry while its hatcheries were coming on line. Contributions from the fish health and salmon enhancement programs are detailed in other articles in this *Review.*

In 1974, the department entered into a long-term agreement with the Atlantic Salmon Federation to conduct research on salmon genetics and the selection of strains with improved traits for sea ranching (a strategy where salmon smolts are released and adult salmon recaptured upon their return) and wild stock enhancement. In 1984, the objectives of the Salmon Genetics Research Program (SGRP) were expanded to include research in support of sea-cage culture. Today, three major strains of salmon are being developed: one to serve the salmon culture industry, with emphasis on such traits as improved growth, delayed maturation, and disease resistance; a second to meet sea-ranching requirements having high rates of return; and a “biotechnology” strain, through which novel technologies, such as sex reversal, polyploidy, and sperm cryopreservation, can be tested for future application. The SGRP is now the “primary breeder” on the broodstock development program of the New Brunswick Salmon Growers’ Association.

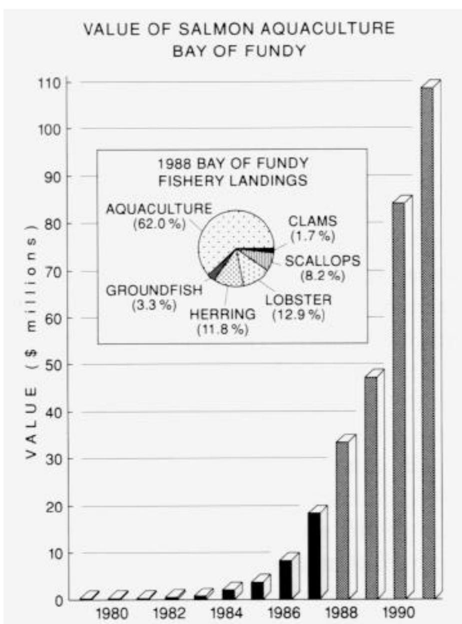

Figure 3. The value of the salmon aquaculture industry in the Bay of Fundy, beginning in 1979 and projected through 1991.

Another successful initiative was the establishment in 1985 of the Salmonid Demonstration and Development Farm (SDDF), based on the highly successful “experimental farm” model used in agriculture, where practical problems of economic significance are addressed (Cook, 1987). A farm with 16 sea cages and a land-based office/laboratory was established in the heart of the local salmon sea-cage industry. Trials were conducted to determine the effects on salmon growth and survival of different sizes and ages of smelts, feed formulations, feeding regimes, holding densities, and other husbandry practices. The data generated from these trials have provided salmon growers with invaluable operational information, reassured the lending institutions, and provided benchmarks on the performance of Atlantic salmon in marine culture conditions. The need to test new cost-effective feed formulations and labour-saving feeding methods, improve product quality, and provide a secure grow-out facility for departmentally sponsored research projects, such as the SGRP, place high demands on the SDDF’s experimental facilities. In 1989, the New Brunswick Salmon Growers’ Association assumed the management of the SDDF. A new marine site has been approved, and the next phase of the program is expected to commence in 1990.

The supply of smolts is a key factor in commercial salmon culture. The smoltification process, when salmon parr raised in freshwater adapt physiologically to life in the sea, is complex; some parr smoltify after less than one year in freshwater, whereas others may take two or more years depending on their genetic makeup and the environmental conditions. The time during which smolts can be successfully transferred to seawater is very brief, usually a two-week period in early May. A large proportion of these smolt-sized salmon will not adapt to seawater and will remain as parr for another year. Such smolts are referred to as 2+ smolts, as they have lived for more than two years in freshwater. They will require an extra year

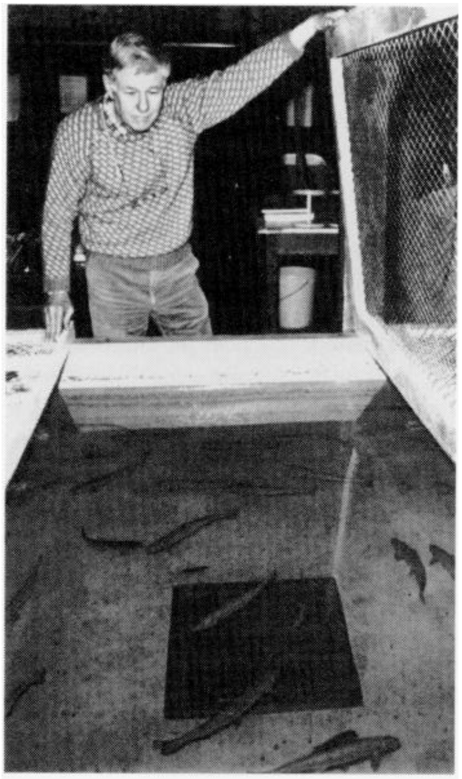

Figure 4. Experimental trials on 0+ salmon smolts at the St. Andrews Biological Station.

of hatchery expenses and, accordingly, are more expensive to purchase. At the St. Andrews Biological Station, research is focused on the factors controlling smoltification and is exploring ways to accelerate its onset and extend the "window" during which smolts can be transferred to seawater. This research has produced experimental lots of smolts in less than a year (0+ smolts - Fig. 4).

In salmon culture, feed accounts for a third of production costs, in spite of the exceptional conversion rates now experienced, where 1.3 kg of fish feed can produce 1 kg of salmon. The basic moist diet used by the majority of salmon growers was developed as a result of research carried out at the Halifax Fisheries Research Laboratory. Dry salmon diets have been developed, as well as specialized diets for fish at different stages of development, such as broodfish, which have individual dietary requirements. Current studies are looking at the role of vitamins in fish feeds, at dietary constituents that assist in disease prevention, and at diets for salmon broodstock. The demand for information on salmon nutrition is open ended, as the economic viability of the industry depends on costs, availability, and performance of feed.

The rapid growth of salmon farming, especially in the Bay of Fundy (Figs. 2 and 3), has resulted in concern for the impact of aquaculture on fish habitat and the marine environment. More information is required in order to answer the question of how many salmon can be reared without adverse ecological effects. The approved level of production in the area of the Bay of Fundy currently being exploited is 4.4 million fish. In 1990, 3.1 million salmon occupied 1,000 sea cages at 47 leased sites with a total area of 280 hectares. The surface area of the cages alone was 18 hectares. For several years, scientists at St. Andrews have studied the benthic ecology, phytoplankton, and water quality at salmon farms in L'Etang estuary. In 1988, oceanographic studies were started, and in 1989 this estuary, the most intensive salmon grow-out area in eastern Canada, was selected for the development of a comprehensive ecological research program coordinated by scientists from BIO. They plan to develop a model that will quantify the holding capacity of L'Etang estuary and to develop principles that will find application elsewhere.

The success of salmon culture has encouraged the study of other marine species with economic potential. A new research program was initiated at the St. Andrews Biological Station in 1987 on the culture of marine fish, particularly Atlantic halibut. Considerable scientific effort has already been devoted to the culture of this species, particularly in Norway. In nature, halibut breed at great depths and have very small larvae. Scientific attention has focused on the extended swim-up period and the problems of feeding larvae synthetic food. At St. Andrews, a halibut broodstock holding facility has been built, broodstock have been successfully collected and maintained, and experiments will soon commence on spawning and the incubation of the early life stages. The holding of juvenile halibut in modified herring weirs has been explored with some success, and preliminary studies are underway on striped bass, lumpfish, and eels.

Shellfish culture

Four species of molluscs are currently under cultivation in the Scotia-Fundy Region. These are the American oyster *(Crassostrea virginica)* and the blue mussel *(Mytilus edulis)*, both of which are indigenous to the Maritimes, and the European oyster *(Ostrea edulis)* and the bay scallop *(Argopecten irradians)*, which were introduced to the region. Culture methods for two other indigenous species, the giant scallop *(Placopecten magellanicus)* and the quahog *(Mercenaria)*, are under development.

The blue mussel is the most widely cultivated shellfish species in Scotia-Fundy. Research is underway to determine the nature of two different varieties of mussels growing together in Nova Scotia waters (Fig. 5). One variety, believed to be *Mytilus trossulus*, exhibits slower growth and a smaller maximum size, and its shell breaks more easily during declumping, grading, and packing. The results of this research could have a strong influence on the industry, as methods of seed collection, restocking, and harvesting may have to be modified to eliminate unproductive labour and capital investments and to reduce quantitative and qualitative losses that occur as a result of breakage at harvest.

The recently introduced bay scallop depends on hatchery-produced seed and can produce a marketable crop in one year. It is the only cultivated mollusc that does not require farmers to risk their stock over winter. A cooperative project between staff at the Halifax Laboratory and a scientist from DFO's Gulf Region is investigating the transmissibility of a parasite from this scallop to other wild and cultivated species. The results will provide the basis

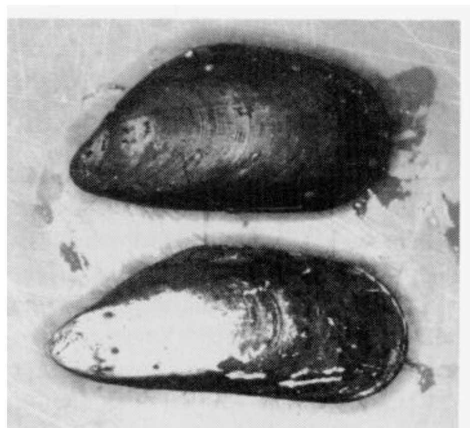

Figure 5. Two varieties of mussels growing in Nova Scotia waters. Top: Mytilus edulis. *Bottom:* Mytilus trossulus.

of guidelines for future transfers of this species to new grow-out farms. Another project on the bay scallop is aimed at improving the genetic diversity and vigour of the broodstock. Wild bay scallops brought from Cape Cod during the summer of 1989 were bred in quarantine. The objective is to provide shellfish hatcheries with new generations of bay scallops that are free of disease, pests, and parasites. So far, some parents have produced five successful broods of larvae; the resulting juveniles measured 5 mm at the end of January 1990. If shown to be free of disease and parasites, these animals will be added to the existing broodstock.

Reliable supplies of healthy seed are crucial to the successful culture of any species. Until recently, seed from wild stocks was the sole source of supply. Yet, the collection of wild seed allows only for the cultivation of American oysters and blue mussels; it yields unpredictable numbers of seed of a quality which varies from year to year according to weather and other environmental conditions. Fortunately, shellfish hatcheries can now produce seed of several species in quantities which make it possible for aquaculturists to establish production, financing, and marketing plans without having to worry about the success or failures inherent in collecting seed from the wild. Scientists can now concentrate on increasing the adaptability of seed to our farm environments through research on broodstock selection and improvement. Research can also lead to improved diets for conditioning broodstock prior to reproduction, improved growth of larvae and juveniles, and enhanced seed size and quality at the time of transfer to grow-out sites. This should result in faster growth and survival during the grow-out stage and should translate into increased yield and profit for growers. A new molluscan nutrition program has just been started with these objectives in mind. It will use microparticulate encapsulation techniques for dietary formulas tailored to the needs of every stage of the life cycle of cultivated molluscs.

Scientists are not able to anticipate all needs; sometimes they must react to the unexpected and develop solutions to new problems. The bloom of *Nitszchia pungens* which caused the crisis of domoic acid contamination in mussels in the fall of 1987 created an unanticipated demand for information. Among other things, the rate of accumulation of this toxin and its elimination from the tissues of several species of shellfish must be known in order to eliminate all risk to consumers. Results to date show that domoic acid can be eliminated very rapidly and that effective depuration protocols seem attainable (Fig. 6). Such information is important to the consumers, distributors, and producers of shellfish, and it is particularly crucial for existing and prospective growers of bay scallops because this species has a narrow marketing window in the fall. This piece of reactive research, which was conducted in cooperation with the Gulf Region, involves the blue mussel and the bay scallop and will be extended to other commercial species.

Discussion

The demand for information and research in support of the dynamic aquaculture industry is invariably greater than our capacity to supply it. Important scientific challenges stand in line for the attention of the scientific community. The carrying and holding capacity of our bays and estuaries must be determined and the knowledge used to establish finfish and shellfish leasing guidelines which will maintain cultivated biomasses at levels commensurate with the ability of ecosystems to support them. Culture and grow-out methods need to be optimized to ensure healthy profit margins, to improve the competitiveness of farmers, and to lower production costs to a level where a competitive processing sector can be established. The environmental requirements of cultivated species and of new candidates need to be defined and matched with available sites. A scientific basis is required for transfer protocols that minimize the risks of also transferring diseases, pests, and parasites when moving aquaculture stocks between hatcheries and farm sites. These are only some examples of the current need for aquaculture research; the list is by no means complete.

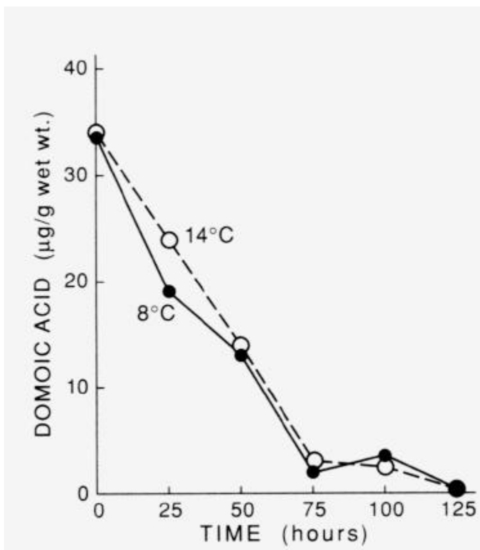

Figure 6. The elimination of domoic acid from naturally contaminated mussels at 8° C and 14° C.

Both the finfish and the shellfish culture sectors face similar scientific concerns which demand attention. The impact of cultivated biomasses and of culture methods on host ecosystems should be monitored and the results used to build predictive models. The knowledge of and the capacity to foresee such effects are crucial for fishermen fearing adverse effects on natural stocks, for prospective growers facing husbandry or investment decisions, for decision makers responsible for coastal zone resources, and for the management of development projects requiring public funds. New applications for leases often face strong opposition from local interest groups, home owners, fishermen, mariners, etc. Such opposition is often falsely based on fears that the proposed culture operation will destroy the value - aesthetic or otherwise - of the site, reduce property values, restrict navigation, or harm an existing fishery. The scientific community can intervene by disseminating existing information more widely and by contributing new information. Increased understanding will allow proponents of aquaculture to present stronger cases for development; an informed public will be a better judge of what is in the public's best interest.

The aquaculture industry provides an important example of how scientific knowledge and technology have been combined to produce a major economic advance within the fisheries sector. This is only a beginning. The farming of marine fish has considerable promise, provided the appropriate biological knowledge can be developed. The shortage of fish and the increasing international competition in traditional fisheries is creating economic disruption and personal hardship in many rural communities. Aquaculture could augment traditional species and provide much-needed employment and stability. The success of salmon culture demonstrates that investment in science can pay off in tangible socioeconomic benefits. Farsightedness is required to anticipate the demand for the science needed to make aquaculture a major contributor to the makeup of the Atlantic fisheries. However, increasing demands for information on the culture of finfish and shellfish species, fish health and habitat, and the interactions with wild stocks have nearly exhausted our capacity to respond. Aquaculture needs a constant flow of new information if it is to expand and prosper; the strategy for meeting these new demands is the challenge.

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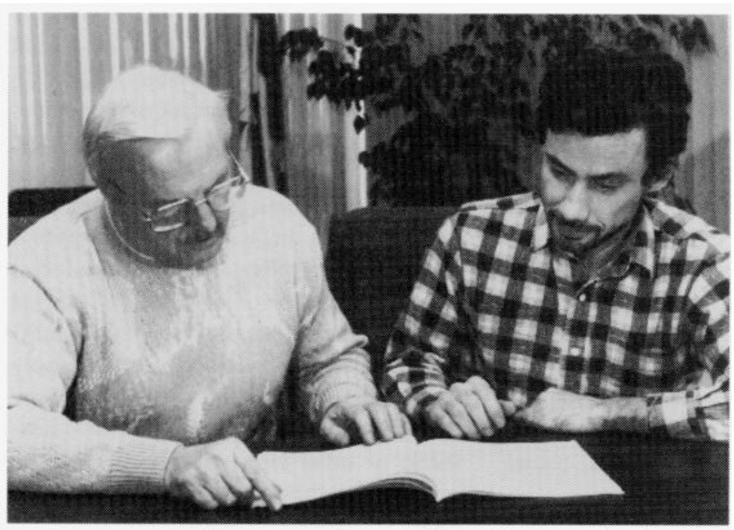
Fish health in aquaculture

J. W. Cornick and G. Olivier



J. W. Cornick and G. Olivier

The term health, in its broadest sense, encompasses all aspects of the well-being of a species, including nutritional status and physiological condition, as well as the presence or absence of infectious disease (Meyer *et al.,* 1983; Post, 1987). In the Maritime Provinces, as in other areas, most of the recorded information available on the health of aquatic species relates to those species under intensive culture, because it is most readily observed. Extensive data are available on the health of cultured finfish, having been gathered to satisfy existing disease control regulations, policies, and programs.

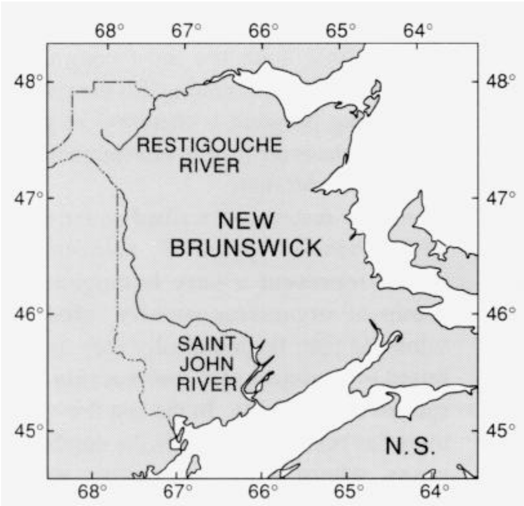
Of all losses in aquaculture facilities, those due to infectious disease are probably the most drastic and certainly the most costly. Besides the value of stock lost to disease each year, vast amounts of money are spent on disease prevention and treatment. In the Maritime Provinces, conservative estimates have placed annual disease-related losses as high as 40% in some finfish culture facilities. As might be expected, the majority of disease problems occur in areas of highest aquaculture activity. The spread of disease is most often related to the transfer of stocks between facilities.

This paper will discuss the diagnosis and control of, and research into, the diseases currently having an impact on finfish aquaculture in the Maritime Provinces, as carried out at the Department of Fisheries and Oceans (DFO), Biological Sciences Branch, Fisheries Research Laboratory, in Halifax.

Diseases

The principal diseases affecting cultured finfish species in the Maritime Provinces include the bacterial diseases of furunculosis, bacterial kidney disease (BKD), vibriosis, and, to a lesser extent, enteric redmouth disease (ERM) (Cornick, 1990). In freshwater hatcheries, furunculosis, BKD, and ERM are the most significant. In sea cages, vibriosis, furunculosis, and BKD cause the most problems. The prevalence of the diseases varies between provinces, being highest in New Brunswick, and is generally a reflection of the relative degree of stock transfer associated with aquaculture activity.

Typical furunculosis has been identified only in New Brunswick, where it has occurred in both freshwater and salt-water sites. Atlantic salmon are most commonly affected, and the disease is endemic on several major river systems, such as the Saint John and Restigouche rivers (Fig. 1). It has been identified in 8 facilities, where it is an important factor limiting the supply of smolts. In spite of careful monitoring of all smolts transferred to marine sites, furunculosis did reach cage facilities in the Bay of Fundy in the past: once in 1985 at 5 sites, when carrier tests failed to detect in-



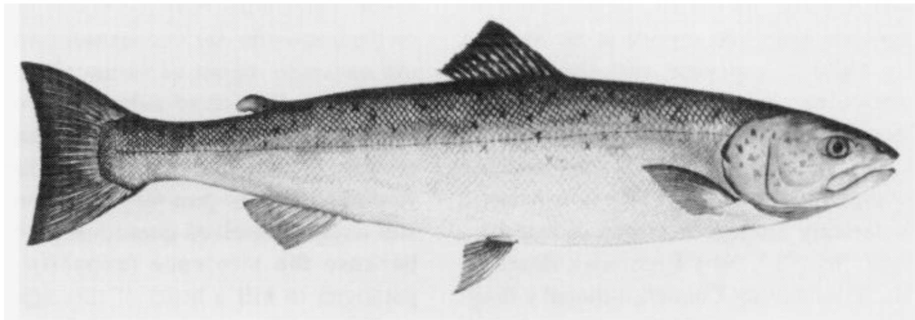


Figure 1. The map shows the Saint John and Restigouche rivers, in New Brunswick, where typical furunculosis is endemic. To the right is a full-grown, uninfected Atlantic salmon.

fected fish, and again at 3 sites in 1989, when smolts were inadvertently infected through the use of a nonsterile commercial vaccine. In 1985 the disease was eradicated by the use of interim medication and subsequent stock removal. Last year, the disease was controlled by medication at all sites but is not totally eradicated.

Clinical BKD has been identified in both freshwater and marine culture facilities in New Brunswick and, to a lesser extent, in Nova Scotia. It is primarily a disease of Atlantic salmon, although trout species may be susceptible. The disease may progress rapidly in freshwater but tends to be slower in salt water, where it persists as a chronic infection with low-grade mortality. No vaccine is effective against the disease and it responds poorly to antibiotic treatment. Because of this, all outbreaks in freshwater have normally resulted in stock destruction. In marine cages it has, in the past, been managed by yearclass separation and the careful screening of incoming smolts. The disease is particularly troublesome because it is vertically transmitted through the egg. In the past this was an important factor limiting the availability of salmon eggs in New Brunswick. Prior to 1987, clinical BKD was fairly common in marine broodstock in New Brunswick, and stocks had to be carefully screened to prevent transmission through the eggs. Recently, however, more clean broodstock have become available, and more careful screening programs have been instituted. Despite this fact, last year the disease was responsible for the quarantining of a major smolt facility, resulting in a shortfall of approximately 0.5 million smolts. The source of the infection was traced to infected eggs which had evaded detection under the broodstock monitoring program. In Nova Scotia this disease is confined to Cape Breton, where it exists at one hatchery and a single marine cage site. In both cases, the disease is under control and eradication attempts are underway.

Vibriosis is most commonly found in the marine environment, where it affects salmon and trout. Both *Vibrio anguillarum* biotypes 01 and 02 have been associated with disease outbreaks in the Maritime Provinces. Prior to 1983 the disease in salmon was primarily associated with biotype 01, but since 1985 biotype 02 has been the exclusive agent. The disease is generally well controlled by chemotherapy and/or vaccines. Strains commonly develop resistance to antibiotics, however, requiring periodic changes in the drug used. Initially, oxytetracycline was the drug of choice, but recently oxolinic acid has been widely used. Available vaccines were relatively effective against vibriosis until a new strain emerged recently. A new vaccine containing this strain was recently introduced which appears to be more effective.

ERM is found most commonly in salmon and trout in freshwater but can be transferred to sea water in infected fish. It has been isolated from salmon in Nova Scotia and New Brunswick, usually in the absence of any clinical symptoms. However, it caused serious epidemics on two occasions in Nova Scotia during 1987: it caused a severe outbreak in salmon and trout in Cape Breton, resulting in the eventual destruction of a large number of fish; and it was responsible for heavy losses in salmon smolts in a research institution. The disease responds well to treatment with oxytetracycline.

Other diseases occur in cultured fish in the region but are of less importance. Infectious pancreatic necrosis virus (IPNV) is present in various fish species in all three provinces, but usually occurs in the carrier state and does not result in significant losses. Other minor diseases occur, such as myxobacterial infections and protozoan parasite diseases *(Costia* and *Hexamita)* which are opportunistic or seasonal in nature.

Diagnostics

Supporting diagnostic services are essential to all developing aquaculture industries (Cornick, 1989). In 1976, DFO established its Fish Health Service Unit (FHSU) diagnostic laboratory in Halifax to provide diagnostics in support of the department's disease regulation and policy mandate, as well as to provide diagnostic and consultation services to a developing aquaculture industry in the region as resources permitted.

The provision of diagnostic services has not kept pace with the development of aquaculture. Between 1976 and 1986 the DFO-FHSU lab was the only diagnostic service available in the region. During that period, requests for services increased tenfold. With the cooperation of DFO the New Brunswick Department of Fisheries and Aquaculture (NBFA) developed a diagnostic-extension service at St. Stephen in 1986 to service the developing aquaculture industry in the Bay of Fundy. Another important diagnostic service became available in 1986 with the formation of the Fish Health Unit at the new Atlantic Veterinary College in Prince Edward Island. In 1987, New Brunswick Research and Productivity Council initiated a diagnostic service out of Fredericton, and 1989 saw yet another newcomer, Moore-Clarke in St. Andrews, New Brunswick, providing a consulting and diagnostic service to its customers in the region.

The increase in diagnostic services has some very distinct advantages for the development of aquaculture in the region. There is now a wider range of expertise available to the culturist; diagnostic labs can share information, resulting in less duplication and increased efficiency; more disciplines are available to bring to bear on disease problems; more opportunity exists for case referrals and consultations by diagnosticians; and more sources of information are available for DFO's disease inventory for the region.

There are, however, some problems besetting aquaculture diagnostics. There is a need to develop guidelines governing the release of confidential diagnostic information; rules should be developed to ensure the immediate, mandatory reporting of serious diseases by all diagnosticians; diagnostic techniques should be standardized to simplify the interpretation of information exchanged between laboratories; and certain diagnostic procedures currently in use are difficult to interpret (e.g., the fluorescent antibody test for BKD in tissues) and need more research. Notwithstanding current problems, the future for diagnostics looks promising.

Research

Fish diseases can be caused by several microbiological and biological agents (bacteria, viruses, and parasites), nutrition (e.g., vitamin deficiency), and environmental factors (temperature, pollution, etc.). Research in fish diseases comprises two major topics. The first one is the study of the pathogen itself, which involves identifying the pathogen, the species of fish affected, and the disease mechanism, and comparing different strains of the agent. Our studies have focused primarily on the bacterium *Aeromonas salmonicida,* the causative agent of furunculosis, an important disease of salmonids in the Maritime Provinces. Although research on this pathogen has been conducted worldwide for the past 40 years, there are still many unresolved questions, probably because the virulence (capacity of a pathogen to kill a host) of this agent is multifactorial and complex. We know that it can produce several toxins that can cause severe damage to the host, but we still don't know the exact mechanism by which this is achieved. Our investigations have revealed an as yet unreported factor produced by this bacterium. We have found that live *A. salmonicida* bacteria can kill the phagocytic cells (macrophages) of fish. We do not know exactly how this is done, but such a pathogen has a tremendous advantage over the host because phagocytosis (an important biological function of macrophages) is one of the most important defense mechanisms of fish against disease.

Antibiotic resistance of the various strains, coupled with the use of *A. salmonicida* bacteriophages (viruses that infect bacteria), have enabled us to study the epidemiology of furunculosis in the Maritimes since 1983. We have shown that furunculosis is established in wild fish populations of the Saint John and Restigouche river systems in New Brunswick; therefore, hatcheries using water from these rivers are at risk of contracting this disease. We have confirmed that, at least in the Maritimes, furunculosis is often transmitted through carrier fish. These fish actually harbour the pathogen but show no clinical signs of the disease, and if they are analyzed by normal bacteriological techniques they appear healthy. These findings have led us to the use of a detection program using corticosteroids (substances that depress the immune system, thereby allowing disease to develop) and stress (high water temperatures) to test for the presence of carriers in a population before the fish are sent to sea cages. In verifying the antibiotic profile of *A. salmonicida* isolates over the last 10 years, we have also noticed a trend in the resistance of these bacteria to oxytetracycline and oxolinic acid, the most commonly used antibiotics for treating this disease. A monitoring program is therefore in place and all isolates are now tested routinely for antibiotic resistance.

All the research described so far deals with strains of typical *A. salmonicida* which represent a very homogeneous group of organisms usually infecting salmonid fish; taxonomically they are referred to as strains of *A. salmonicida* subspecies *salmonicida.* In the last few years there has been an increase in the number of cases where atypical strains of *A. salmonicida* (subspecies *achromogenes* and *nova)* have been found to cause disease in salmonid as well as nonsalmonid fish. It was found that atypical *A. salmonicida* strains are very heterogeneous biochemically and that their taxonomic position may have to be reassessed. When the virulence of some of these isolates was tested, some were nearly as virulent as typical isolates. Our findings also indicate that some atypical isolates are of marine origin, suggesting that these strains may cause problems for the aquaculture industry.

The second major topic in fish disease research is the study of the immune system of the host. Research in this area is lagging behind other types of research, although there is strong evidence that it is needed if more effective vaccines are to be developed in the future. To understand the importance of this type of research we only have to look at the commercial vaccines against various bacterial diseases. What is surprising is that even if we know that vaccines can confer protection, we actually don't know how they work or, more precisely, which arm of the immune system they stimulate. In this type of research we are interested in finding out how fish respond to different antigens and in detecting which type of immune system is stimulated following a certain vaccination procedure. For years it was thought that if vaccines could induce the production of antibodies (humoral immunity), this response was a reliable indicator of the protection conferred, but our findings and those of others are now challenging those results. In the case of furunculosis, we have provided evidence that if the cellular immune system is stimulated, very good protection can be elicited. These results clearly indicate our need to better understand the immune system of fish if we want to improve the efficacy of vaccines.

Disease control

Two important approaches to disease control include disease regulations and fish health management programs (Cornick, 1987). The former seeks to control the geographic spread of diseases by controlling the transfer of infected stocks. This is usually achieved by governments through regulations, policies, and specific disease control programs involving routine disease inspection procedures. The latter includes fish health management programs carried out by the culturist, including such practices as husbandry, vaccination, and chemotherapy to prevent or control disease at the particular facility.

In the Maritime Provinces, disease transmission related to stock transfer is controlled through a number of federal or cooperative federal-provincial programs (Cornick, 1989). All involve stock inspection and clearance prior to transfer. Diagnostics in support of these programs are carried out by the DFO-FHSU lab in Halifax, and the NBFA lab in St. Stephen, New Brunswick.

The National Fish Health Protection Regulations, introduced by DFO in 1984 and currently administered by that department, control the international and interprovincial introduction of a number of serious diseases. This is achieved through a certification and permit system involving the inspection of facilities by the DFO-FHSU lab. Since 1970, no major fish diseases have been introduced into or spread among the Maritime Provinces, due in large measure to these regulations.

The Maritime Provinces Regional Fish Health Policy is administered by DFO Scotia-Fundy Region, under agreement with DFO Gulf Region and in cooperation with provincial governments and the private sector. The policy controls the spread of three important diseases of limited distribution - furunculosis, BKD, and ERM - between watersheds within Maritime Provinces. All lots of fish to be moved require inspection by the DFO-FHSU lab. Fish are moved only between watersheds of similar disease status. Since 1983, no diseases have been transferred by fish inspected under this program.

In 1985, two specific programs were developed by DFO Scotia-Fundy Region in cooperation with NBFA to deal with two particular disease-related problems affecting the aquaculture industry in New Brunswick. Diagnostics in support of the programs are carried out at the DFO-FHSU lab in Halifax and at the NBFA lab at St. Stephen. A Furunculosis Carrier Testing Program was designed to limit the spread of furunculosis from freshwater sites to marine cage facilities in carrier smolts. Because the carrier or latent state of this disease is not detected by normal microbiological culturing methods, all smolts going to cages are prescreened using a special immuno-suppression technique. A Broodstock BKD Monitor Program was developed to control the transmission of BKD in salmon eggs. It involves the use of sensitive fluorescent tests to screen reproductive fluids from individual salmon at spawning time. Eggs from matings involving positive fish are eliminated. Initially, diagnostics for this program were carried out by the DFO and NBFA labs, but more recently individual culturists have assumed responsibility for having the diagnostics done privately. This program has been generally effective, although several recent outbreaks of BKD are suspected to have been caused by a lapse in this program.

Prevention is the most important aspect of fish health, but, as in any intensive culture operation, we must realize that disease can occur and that if it does there are several options to consider. These options include eradication, vaccination, and chemotherapy. The choice of one option over another is not easy to make and depends on a variety of factors. For example, in cases where an exotic disease (a disease that has never before been found in Canada) has been confirmed, the only option in most instances would be the eradication of the disease by the destruction of all stocks of fish and the total disinfection of the hatchery where the disease was found.

For other types of infectious diseases which are widely distributed around the world, good husbandry is the most important aspect of prevention, but if outbreaks occur, vaccination and chemotherapy are then considered. If an effective vaccine is available, fish should be vaccinated before they are put in the environment where the disease occurs. In the Maritimes, all Atlantic salmon smolts are vaccinated against vibriosis before they are sent to marine cage sites because vibriosis is endemic in the sea. In some cases, even if fish have been vaccinated the disease can still strike and cause mortalities in the population. When this happens there remains only one alternative. and that is to treat the fish with an antibiotic, usually mixed with the food. One has to remember that the use of antibiotics should be closely monitored and that one of the main problems associated with chemotherapy is the development of resistant strains. This represents only a summary of the options available in the case of disease outbreaks, but it should be borne in mind that each case could be different and the final course of action should be carefully analyzed.

Conclusion

In spite of the recent rapid development of aquaculture in the Maritime Provinces, the disease-related problems encountered appear to be under control. This is due largely to the implementation of effective disease-control strategies, ongoing disease research, and advances in diagnostic capabilities in the region, as well as good cooperation between federal and provincial governments and the private sector.

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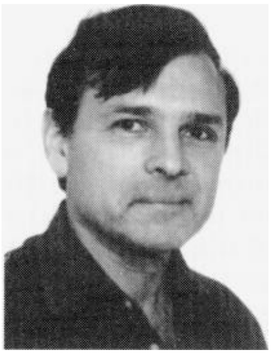
Programs of the region’s fish culture stations

G. J. Farmer



G. J. Farmer

The Freshwater and Anadromous Division of the Biological Sciences Branch of the Department of Fisheries and Oceans operates six fish culture stations, which have a total annual production of 1.7 million juvenile Atlantic salmon *(Salmo salar).* The salmon are utilized for purposes of salmon enhancement, in support of the aquaculture industries in New Brunswick and Nova Scotia, and for research. Salmon production is carried out in freshwater at the Yarmouth, Mersey, Coldbrook, and Cobequid stations in Nova Scotia, and at the Mactaquac and Saint John stations in New Brunswick. Half of the juvenile salmon produced each year are distributed as parr and half at the smolt stage. Smolts range in length from 12 to 20 cm and are able to live in seawater, whereas parr are less than 12 cm long and cannot tolerate seawater. When parr attain a length of more than 12 cm, they undergo the parr-smolt transformation and begin their downstream migration to the sea. Most stations have been modernized and expanded during recent years, which has enabled smolt production to be doubled and smolts to be produced in one year, rather than two as in the past.

Salmon production methods and facilities: two examples

Mersey Fish Culture Station: The Mersey Fish Culture Station (FCS) is the largest salmon culture facility in Nova Scotia and is located on the Mersey River near the community of Liverpool. The station has 20 concrete ponds measuring 7.6 m by 7.6 m, and 16 concrete ponds measuring 11 m by 11 m (Fig. 1). The ponds have rounded comers, contain water 50 cm deep, and are referred to by salmon culturists as “swede ponds”. Annual production at the station is 300,000 one-year-old salmon smolts. Water is withdrawn from the Big Falls headpond by dual intakes and delivered to the ponds by gravity flow in a polyethylene pipeline 30 cm in diameter. One of the intakes is located at a water depth of 2 m, and the other is on the bottom of the headpond at a depth of 8 m. Because the surface temperature of the headpond ranges from 22 to 27°C during the summer, cooler water is withdrawn from a depth of 8 m and provided to the salmon from June until September. Surface water can also be provided by a transite pipeline 30 cm in diameter.

Adult salmon are held at the Coldbrook FCS in Kings County until November, when they are spawned (that is, the staff manually express the eggs and milt) and the fertilized eggs from 12 river stocks are transported to the Mersey FCS. The eggs are deposited on perforated, rectangular trays which are placed in fibreglass troughs in the hatchery building. The water that is supplied to the troughs is not heated. The eggs are eyed (that is, the eyes of the embryos become visible) by early February, at which time they are transferred to upwelling incubation boxes which contain layers of a plastic material. Hatching occurs early in April, and the salmon, referred to at this stage as alevins, remain relatively inactive while in the plastic substrates and efficiently utilize their yolk material for growth. The yolk is absorbed by the middle of May, when the young salmon, which weigh 0.15 g each, are transferred to the outdoor 7.6 m ponds. Each outdoor pond holds 50,000 salmon, which are provided with a dry, artificial diet at half-hour intervals during daylight hours. Water temperatures at that time must exceed 10°C in order to stimulate feeding.

The food intake, conversion efficiency, and growth of juvenile salmon is maximal within the 15 to 18°C temperature range. Because of the geographic location of the Mersey FCS and because water can be withdrawn from different depths of the headpond, optimal temperatures for the growth of salmon are available six months of the year (Goff and Forsyth, 1979). During the period from May through November, the number of salmon in each of the rearing ponds is reduced at regular in-

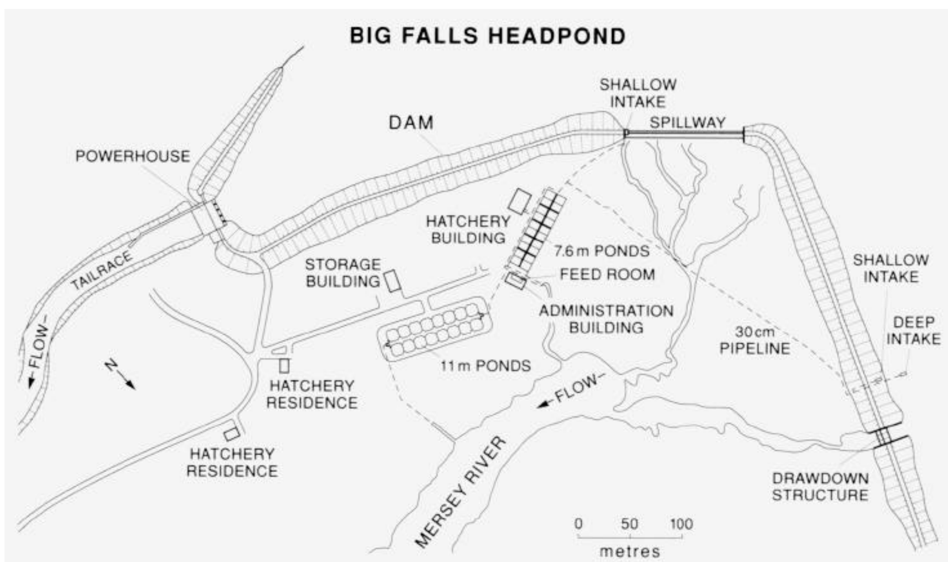


Figure 1. Mersey Fish Culture Station.

tervals to maintain the desired density levels, and all 36 ponds are utilized for salmon production. Salmon density is maintained at 5 kg/m^2, and water flow is maintained at 1.5 L/kg of salmon/minute. The smaller salmon are removed from the ponds during October and the 300,000 largest salmon (or 60%) are retained. The salmon continue to grow until November, when temperatures drop below 10°C, reaching 2°C by December. The salmon have an average weight of 45 g by April or May, at which time they complete the parr-smolt transformation and are distributed. The Mersey FCS is unique because a significant number of one-year-old salmon smolts can be produced at that location without artificially heating the water to accelerate the growth rate.

Mactaquac Fish Culture Station: The largest and most recently constructed hydroelectric dam on the Saint John River in New Brunswick was completed in 1968. The dam is located 3 km above the head of tide at Mactaquac and it created a reservoir 97 km long. This has resulted in the loss of a significant area of salmon habitat and the potential elimination of populations of fish that used to migrate to areas above the Mactaquac Dam. Fish collection facilities were therefore incorporated in the dam, and the Mactaquac FCS was constructed 2.5 km downstream to compensate for the loss of salmon habitat. When the station was completed in 1968, it had the capacity to produce 225,000 two-year-old Atlantic salmon smolts. The production of significant numbers of one-year-old smolts was not possible because optimal water temperatures for the growth of salmon were available only 4.5 months of the year. During 1983/84, an accelerated rearing facility was constructed to utilize the warm waste water collected from the generating units at the Mactaquac Generating Station. The development of eyed eggs and alevins is accelerated by the use of the warm water, and the salmon begin feeding during April, two months earlier than was possible in the past.

River water used to cool the thrust bearings and stators of the six generating units is collected in two pipelines, through which it flows by gravity to a pump building located adjacent to the generating station (Fig. 2). A supply of cooler (not warmed) river water collected from two of the penstocks also flows by gravity to the pump building in a single pipeline. All of the warm water enters a mixing chamber in the pump building, while entry of the cooler water is regulated by an automatic butterfly valve operated by a pneumatic temperature controller. The mixed, warm water flows to a sump chamber in the building and is pumped 200 m to a headtank building by a number of vertical turbine pumps. The warm water which enters the headtank building passes through an automated sand filter and then to 30 packed columns before being discharged into a concrete headtank. The filter re-

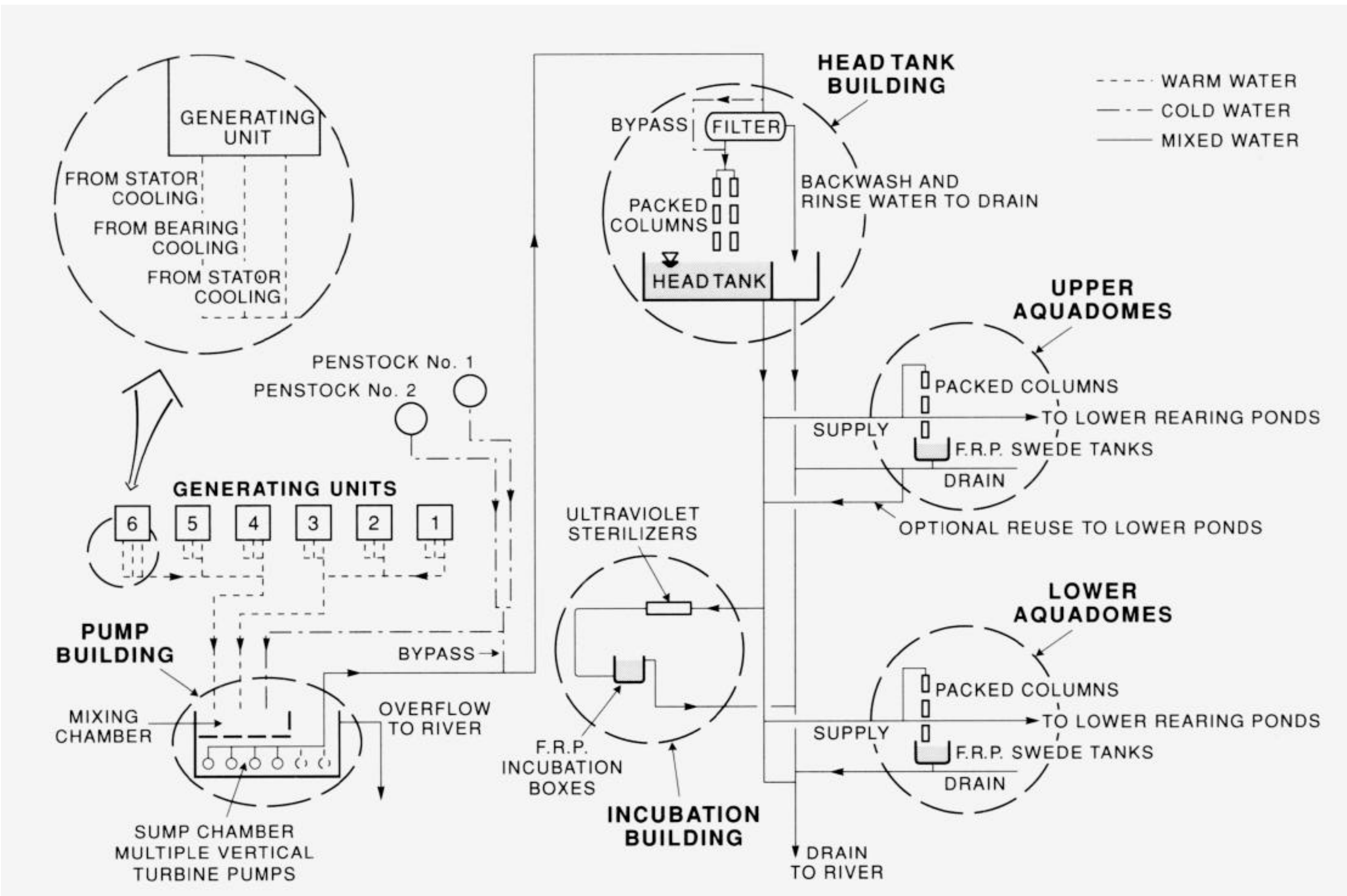


Figure 2. Flow diagram of the accelerated rearing facility, Mactaquac Fish Culture Station.

duces the concentration of suspended solids, and the packed columns reduce the total gas pressure. The warm water then flows by gravity to the incubation building or to four aquadomes. Water (at 6°C) which enters the incubation building passes through two ultraviolet water sterilizers and then to a number of upwelling incubation boxes which contain eyed eggs and alevins. The salmon are removed from the upwelling boxes during early April and transferred to 3 m by 3 m fibreglass tanks enclosed in the aquadomes. The four aquadomes are prefabricated greenhouses, each containing 18 of the 3 m tanks. Use of the warm water (15°C in these facilities) enables production of 720,000 2-g parr by mid-June of each year, 67 to 71 days after the initiation of feeding. The parr are then transferred to the Mactaquac FCS, where they are reared in outdoor concrete ponds. Grading occurs during the fall, and 400,000 salmon are retained for distribution the following spring as one-year-old smolts. The practice of using the warm water from the generating station to accelerate the growth and development of the salmon has resulted in a doubling of smolt production at the Mactaquac FCS.

Salmon enhancement programs

The populations of some salmon stocks native to the Scotia-Fundy Region have declined because of overexploitation, while others have been reduced or eliminated as a result of losses in the productive capacity of their freshwater habitats. Watt (1989) estimates that the productive capacity of Atlantic salmon habitats in eastern Canada has been reduced by 16% since 1870, a loss that is attributable to agricultural practices, water diversion and obstruction, the creation of impoundments, and acidification. Salmon habitat loss has been particularly severe within the Scotia-Fundy Region, where there has been a 50% reduction in productive capacity (Watt, 1988). As a result, the natural production of Atlantic salmon within the region has not satisfied the demands of the commercial and recreational fisheries. The region's commercial salmon fishery has therefore been closed, and catch and season limits have been imposed on recreational fishermen.

During the spring of 1990, a total of 765,400 hatchery-reared smolts were released in 28 of the region's rivers (Table 1). Whenever possible, the smolts released in a particular river are the progeny of adults native to that river. The smolts migrate to sea, where they spend from one to three years before returning as adults to spawn in the river in which they were released. About one-third of the adult salmon which return to the region each year exist as a result of the salmon enhancement effort. These adults help satisfy required spawning escapements - that is, they provide the numbers necessary to maintain the salmon populations in the rivers. They also contribute to the recreational fishery, which consists of 26,500 recreational fishermen in Nova Scotia and New Brunswick who expend about 98,000 rod-days of effort each year to capture 20,000 adult salmon in 100 of the region's rivers (O'Neil *et al.,* 1989).

Carlin tags are attached to about 10% of the smolts released each spring. Using monofilament, these small plastic tags, inscribed with a return address, are attached to the smolts below the base of the dorsal fin. A $10 reward is paid for the return of any tag removed from an adult salmon and for information pertaining to the size of the salmon and the method, time, and location of capture. The tagging program has contributed to our understanding of the migratory patterns of various stocks, the contribution those stocks make to various fisheries, and the factors which influence the survival and age-at-maturity of hatchery-reared smolts. For example, the survival of hatchery smolts is influenced by a number of factors, such as their size, the formulation and quality of hatchery diets, rearing practices, release timing, river discharge, and the abundance and distribution of predators at the time of release. Rates of interception in commercial fisheries outside the region vary for different salmon stocks and are influenced by their age-at-maturity and by the route and timing of ocean migrations in relation to the intensity, timing, and location of coastal fisheries.

The major marine feeding area for many of our salmon stocks is believed to be the Labrador Sea (Reddin, 1988). Seasonal shifts in the distribution of salmon in the northwest Atlantic appear to be influenced by sea-surface temperatures. In spring, salmon are concentrated in the southern Labrador Sea and around the Grand Bank, while, in the summer, nonmaturing salmon move into the Davis Strait off western Greenland. The salmon harvested in Greenland are those that have spent one year at sea and would have returned home as two-sea-year salmon. The Newfoundland and Labrador fisheries harvest salmon of all sea-ages, while the coastal fisheries of Nova Scotia and New Brunswick primarily intercept maturing one- and two-sea-year salmon as they return to their home rivers. In contrast, stocks from the upper Bay of Fundy first return home to spawn after one year at sea

Table 1.
Smolts for release during 1990

Gulf Shore, Nova Scotia	
Margaree River	16,200
Cape Breton East	
Grand River	18,400
Salmon River (Mira)	8,100
Eastern Shore	
St. Mary's River	23,500
Liscomb River	25,000
Moser River	20,300
East Sheet Harbour	10,000
West Sheet Harbour	6,000
Musquodoboit River	21,800
Southwestern Nova Scotia	
Sackville River	10,000
Gold River	15,300
Mushamush River	10,000
LaHave River	40,000
Petite Riviere	10,800
Medway River	50,400
Mersey River	10,000
Clyde River	10,000
Jordan River	10,000
Tusket River	45,100
Salmon River (Digby Co.)	8,100
Upper Bay of Fundy	
Annapolis River	15,300
Stewiacke River	10,700
Southwestern New Brunswick	
Petitcodiac River	10,000
Big Salmon River	15,000
Hammond River	21,200
Kennebecasis River	10,000
Nashwaak River	19,200
Saint John River	295,000
Total (28)	765,400

and are believed to confine their migration to the Bay of Fundy and, perhaps, the Gulf of Maine.

Salmon aquaculture

The number of marine salmon farms operating within the Scotia-Fundy Region has increased from one in 1979 to 48 in 1989, and lease applications have been made for other sites. During that period, 20 private hatcheries were developed to provide Atlantic salmon smolts to the marine farms. It is projected that 3 million salmon smolts will be sold to marine farms within the region during the spring of 1990. Most of the salmon farms are found in the Bay of Fundy along the coast of southwestern New Brunswick and near Deer, Campobello, and Grand Manan islands. Water temperatures in this area are within the 5 to 13°C range for at least 7 months of the year and generally do not decline below 1°C during the winter. The salmon are fed moist or dry extruded diets while they are in the marine cages and attain a weight of about 5 kg within 18 months. The average mortality rate of the salmon while in the cages has been decreasing and was 12% in 1987 (Cook, 1988). The average salmon farm employs 8 people, has 36 cages, and stocks 2,500 to 3,500 smolts per cage. Smolts cost $3 each, and adults have been marketed for as much as $13/kg (Cook, 1988). At the time of writing, the market price, has declined to $9.50/kg. The primary markets for farmed salmon are the larger urban centres in eastern Canada and the eastern U.S. There are 5 salmon farms in Nova Scotia. Of these, 1 is located in Shelbume Harbour, 2 are in St. Margarets Bay, 1 is in Denas Pond, which is connected to Bras d'Or Lake at Little Narrows, and the last is at the Lingan Generating Station, where salmon are reared in warm waste seawater. Expansion of the Nova Scotia industry has been limited, in part, by the inability to locate protected sites where winter sea temperatures do not decline below -0.6°C, the lower lethal temperature for salmon.

During the early 1980s, when the salmon aquaculture industry was developing, most smolts were supplied by fish culture stations operated by the Department of Fisheries and Oceans (DFO). The number of smolts supplied by DFO increased from 10,000 in 1980 to 248,000 in 1988. The sale of smolts in 1988 accounted for 30% of the smolts produced that year by the department. An additional 547,000 salmon parr were sold to private hatcheries in the region during 1988 in an effort to increase the supply of smolts to the marine salmon farms. Smolts supplied by private-sector hatcheries have generally satisfied industry demand over the past two years. The sale of smolts to the industry by DFO has therefore been reduced, and in 1990 those sales will represent about 8% of DFO's production. At present, support to the aquaculture industry is primarily for the development of broodstocks. Smolts which are the progeny of wild adult salmon that returned to River Philip and the LaHave River in Nova Scotia, and to the Saint John River in New Brunswick, are being produced at the Mersey FCS and supplied to four marine salmon farms in Nova Scotia during each year of a four-year program. The program will enable the Nova Scotia aquaculture industry to develop broodstocks from the salmon stock which performs best under local sea-cage conditions. A source of eggs from the stock exhibiting the best performance traits will then be available to private-sector hatcheries. Salmon presently reared by the New Brunswick aquaculture industry were originally derived from adults that returned to the Saint John River. This stock has demonstrated excellent marine growth and survival rates, and most of these salmon do not mature until they have spent two years in the marine cages. These have been key factors in the success of the New Brunswick industry. Thirty thousand Saint John smolts are presently being produced at the Mactaquac FCS for broodstock development purposes within the New Brunswick industry. The performance of these smolts while in marine cages will be assessed, and broodstock which demonstrate increased growth rates, delayed sexual maturity, and, possibly, improved carcass quality and resistance to some salmon pathogens will be selected as part of the Atlantic Salmon Federation's Salmon Genetics Research Program.

Research

The six fish culture stations in the Scotia-Fundy Region provide juvenile salmon to government, university, and private researchers for their investigations. The salmon have been utilized to develop culture techniques, improve the design of fishways, and develop fish vaccines and salmon diets, as well as for studies of fish diseases and for toxicological and physiological investigations.

In conclusion, the region's fish culture stations will continue to produce juvenile Atlantic salmon in support of enhancement programs, the aquaculture industries in New Brunswick and Nova Scotia, and research. Many of the enhancement programs are conducted in conjunction with recreational fisheries organizations. Staff consult with the aquaculture industry in the areas of seedstock supply, broodstock development, and hatchery site selection and design. All six fish culture stations are open to the public, and between them they receive 15,000 to 20,000 visitors each year. A visitors' facility is presently being constructed at the Mactaquac FCS. The public will be provided with guided tours of the station, and information pertaining to Atlantic salmon biology, management, and enhancement will be available. Literature describing programs conducted at the other stations is in preparation and will be provided to visitors at those locations.

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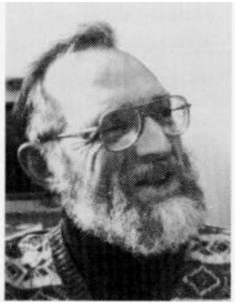
Impacts of acid rain on habitat

G. L. Lacroix, W. D. Watt, and J. F. Uthe

G. L. Lacroix



W. D. Watt

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The phenomenon known as acid rain, and its impacts, are results of factors such as large emission sources in industrialized regions, the meteorological transport system, and the sensitivity of aquatic habitat in eastern Canada. Nova Scotia, because it lies downwind of major emission sources, receives acidic deposition due to long-range transport of airborne pollutants (LRTAP), principally the oxides of sulphur and nitrogen from industrial emissions (Shaw, 1979; Underwood et *al.*, 1987). The local burning of fossil fuels and other local sources can also produce acidic emissions and contribute to the acidification process. Surface waters generally reflect this deposition, but geological and soil characteristics can be important determinants of resulting habitat quality. In base-poor soils, calcium and magnesium may be leached out or taken up by forests and other vegetation, leaving only low concentrations in surface waters. In acid soil conditions, trace metals may be mobilized and leached to aquatic habitat. Organic acids from biological processes also contribute to the acidity of freshwater. Some of the surface waters in Nova Scotia are highly coloured and naturally acidic due to the humic acids from peatland and bogs in river catchments (Gorham *et al.*, 1986; Kerekes *et al.*, 1986; Underwood *et al.*, 1987). The response of aquatic systems to acidic deposition is ultimately a function of the atmospheric supply of strong acid, the geological make-up of the receiving drainage basin, and chemical processes within the watershed.

The acidification of surface waters as a result of acidic deposition from LRTAP has occurred in areas of Nova Scotia where the geology is dominated by granitic rocks, which are very resistant to chemical weathering (Kerekes *et al.*, 1986; Howell and Brooksbank, 1987). It is estimated that 46% of the freshwater habitat surveyed in that province has experienced significant LRTAP acidification, while a further 20% has been acidified by local/natural sources (Howell *et al.*, 1988a). Acidification has been limited in the remaining 34% of habitat because it is situated in areas of low terrain sensitivity. The major zones of acid-rain-induced acidification are in southwestern Nova Scotia, northwest of Halifax-Dartmouth, and in northern Cape Breton Island, whereas the high local/ natural acidification caused by natural organic acids and locally derived strong acids is prevalent in southwestern Nova Scotia, along the eastern shore, and in northern Cape Breton Island. These zones include a number of rivers in the southern upland region, shown in figure 1, which have become more acidic during at least the past 30 to 40 years (Farmer *et al.*, 1980; Watt *et al.*, 1983). The occurrence of lower pH levels in rivers in Nova Scotia during a peak of North American sulphur dioxide emission in the late 1960s and early ’70s suggests that the rivers were responding to loading of mineral acids from LRTAP (Howell *et al.*, 1988b). Most of the rivers which are now chronically acidic have significant seasonal fluctuations in pH, low calcium concentrations, and high concentrations of dissolved aluminum (Lacroix and Kan, 1986). Most also have waters rich in humic acids and have high concentrations of dissolved organic carbon (Oliver *et al.*, 1983). As a result, nonexchangeable (i.e., organically bound) aluminum is the dominant form of aluminum (Lacroix and Kan, 1986). Autumn and winter are the most acidic periods, whereas pH levels increase throughout the spring and summer. Large acidic pulses as a result of snow melting in spring rarely occur because, in most years, little snow accumulates over winter.

The North Atlantic Salmon Conservation Organization (NASCO) recently stressed the importance of determining the influence of the acidification of freshwater habitat on the production of Atlantic salmon (ICES, 1988). The southern uplands region of Nova Scotia (Fig. 1) contains 60 rivers which are known to have supported populations of Atlantic salmon in the 1950s. Thirteen of these rivers are now very acidic (below pH 4.7) and no salmon have been angled from the rivers since early in the 1970s. Angling catch has fallen to about 10% of historical catches (before 1953) in another 18 rivers which are only slightly less acidic (pH 4.7 to 5.0). About 40% of accessible riverine habitat in Nova Scotia is considered vulnerable to acidification, and upwards of 15% of the

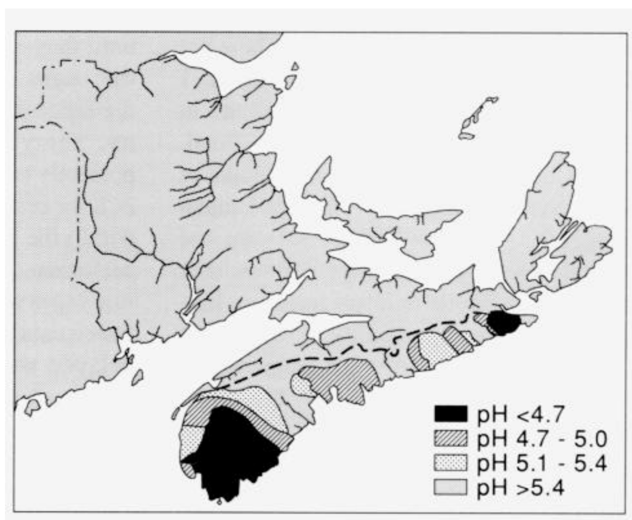

Figure 1. Mean annual pH of salmon rivers in the Maritime Provinces (1979-1985). The area south of the broken line is the southern upland region of Nova Scotia (from ICES, 1988).

available salmon habitat has been lost to acidification since 1950 (ICES, 1988). This represents a high annual loss of salmon to escapement and the fisheries (Watt, 1986).

Indications from the angling catch records for Atlantic salmon, therefore, led to research on the effects of river acidity on freshwater life-stages of the species and on production in order to better establish a link between cause and effects. Results indicate that juvenile salmon are severely affected in acidic rivers of Nova Scotia (Lacroix, 1987a, b, 1989a, b). In figure 2, the range of survival rates through the freshwater life-stages of juvenile salmon at different pH regimes indicates that survival is lowest at low pH levels and survival to the same life-stage is higher at the highest pH levels. There is no survival of salmon past the fry stage below pH 4.7. Survival rates and juvenile salmon densities increase with pH levels above 4.9, and above pH 5.5 the densities are apparently independent of the pH level and survival is similar to values for juvenile salmon populations in unaffected habitat.

Figure 2 shows that alevins and fry are more sensitive to low pH levels than are either eggs or parr. Embryos are generally the least sensitive because of the protection provided by the chorion and perivitelline fluid (Peterson *et al.,* 1980, 1982). Nevertheless, survival of eggs to hatching is a direct function of water pH in spawning beds (Lacroix, 1985a). Newly hatched alevins, with a high ratio of gill surface area to body volume, high metabolic rates, and a lack of protection on the scaleless

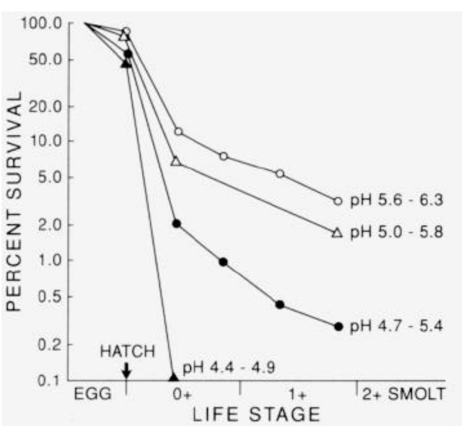

Figure 2. Estimated survival model of Atlantic salmon from egg to smolt in acidic rivers of Nova Scotia representing different pH ranges (from Lacroix, 1987b).

integument, are very sensitive to low pH levels (Peterson and Martin-Robichaud, 1986), and fry are highly sensitive during the transition from dependence on yolk to first feeding (Lacroix *et al.,* 1985). As a result, the rate at which salmon emerge from spawning beds is extremely poor in acidic streams, and no survival is expected below pH 4.7. The mortality of salmon parr during acidity episodes in streams is related to the rate of change in pH and to parr size: small parr are more sensitive than large parr (Lacroix and Townsend, 1987). Critical levels at which parr in rivers of Nova Scotia die are about pH 4.6 for exposures of long duration (20 days) and pH 4.4 for short exposures (5 days or less). In acidic areas where juvenile salmon do not move to less acidic areas downstream before smolting, additional mortality occurs because the transformation from parr to smolt is unsuccessful and mortality is high during chronic exposure below pH 4.7 (Saunders *et al.,* 1983; Johnston *et al.,* 1984; Farmer *et al.,* 1989).

As a result of the effects of acid stress on juvenile salmon density, the production of juveniles and the potential yield of smolts is adversely affected in acidified habitat (Lacroix, 1989a). Total annual production can average 70% less at low pH and fall beyond the lower limit for maintenance of a naturally produced salmon population if minimum levels of pH 4.7 are reached. The production of smolts increases exponentially above pH 4.7, and it is more than 5 times higher at less acidic pH levels and comparable to that for smolts in nonacidic areas. The low production rate in the most acidic rivers is attributable to the very low densities and poorer survival of juveniles at low pH levels, rather than to reduced growth. The growth of parr is often faster in more acidic rivers as a result of the reduced competition for food resources at the lowest pH. A stock could apparently disappear at low pH before there are any serious adverse trophic effects. The low production of smolts in the most acidic rivers is considered insufficient for the continued maintenance of natural salmon populations in those rivers, based on the escapement requirements in rivers of southwest Nova Scotia (Lacroix, 1987b). The high mortality of alevins and fry at first feeding in response to low pH is principally responsible for reduced recruitment and the decline and loss of salmon stocks in acidic rivers of Nova Scotia.

Although salmon is generally used as a model species to document the effects of the acidification of freshwater habitat, research indicates that other fish species are also adversely affected (Lacroix, 1987a). The absence of acid-sensitive species and very low densities of fish characterizes streams at pH 4.5 to 5.0. Like juvenile salmon, cyprinids are usually the most abundant species in the least acidic streams and they are absent in the most acidic streams. The densities of cyprinid species are severely reduced in streams below pH 5.4, and the young age-classes are rare or absent. American eels are generally resistant of acidic conditions, and they are abundant in streams with levels less than pH 5.5, where they account for an increasingly large proportion of the fish biomass at the lowest pH levels. White sucker is also relatively abundant at low pH levels, but its contribution to biomass is unimportant because of the absence of most age-classes older than young-of-the-year. Several other species, such as brook trout and yellow perch, are also found in acidic streams but they are not very abundant, and old age-classes are often absent.

Research has also provided an insight into the mechanisms of effect and the factors involved in reducing fish populations in acidified habitat (Lacroix, 1985b, 1989c; Lacroix and Townsend, 1987; Lacroix *et al.,* 1990). This is especially important because of the confounding effects that increased aqueous aluminum concentrations can have following acidification (Leivestad, 1982; Wood and McDonald, 1987). The physiological responses of juvenile Atlantic salmon and brook trout to chronic acid conditions and to acute acidity typical of episodic events indicate that decreases in plasma sodium and chloride are well correlated with ambient pH, but not with exchangeable aluminum concentrations in rivers. These plasma electrolytes provide reliable indicators of the thresholds for sublethal effects on mechanisms of ionic regulation. Correlations with ambient pH can be used to differentiate between lethal and sublethal responses to acid exposure and, therefore, to indicate the severity of acidification of salmonid habitat. Complete regulation occurs above pH 5.0, and salmonids exposed to water below this pH threshold experience a substantial impairment of ionic regulation. The magnitude of the response is proportional to the level of acid stress, and levels less than pH 4.7 result in the severe loss of electrolytes, often leading to death. Similar electrolyte losses in response to acid stress have also been documented for the smolt stage of Atlantic salmon and for maturing white sucker, alewife, and Atlantic salmon during spawning runs in acidic rivers (Lacroix, 1985b; Farmer *et al.,* 1989; Brown *et al.,* 1990). The physiological changes related to osmotic and ionic regulation that occur during smolting result in a higher sensitivity of salmon smolts than parr to low pH (Lacroix, 1985b).

There is generally no morphological evidence of severe damage or lesions in gill epithelia of salmonids, either during chronic or acute exposure to low pH in acidic rivers of Nova Scotia (Lacroix, 1989b, c; Lacroix et *al.,* 1990). Aluminum, which can cause severe histologic changes in gills, is apparently not a significant factor in the lethal effects observed in most of these acidic rivers. There is no apparent correlation of plasma electrolyte loss in salmonids with exchangeable aluminum in the acidic rivers, and the extent of aluminum accumulation in their gills does not raise the threshold for loss of ionic regulation and for death. The physiological and toxicological effects of aluminum are generally a result of the exchangeable (i.e., inorganic or ionic) forms of dissolved aluminum, which are low regardless of total aluminum because of the extent of binding with organic matter in these waters (Lacroix and Kan, 1986). The mortality of Atlantic salmon alevins in prepared solutions containing aluminum and dissolved organic anions of both synthetic and natural origin was also determined in order to further ascertain the relative importance of low pH and aluminum in organic water characteristic of the acidic streams of Nova Scotia (Peterson *et al.,* 1989). The model indicates that mortality and body accumulation of aluminum increase dramatically as total aluminum concentrations increasingly exceed organic anion concentrations, but that organic anion concentrations in the Nova Scotia waters are high enough in relation to aluminum concentrations to prevent toxicity to salmon alevins, the most sensitive life-stage. Toxicity, therefore, results mainly from the effect of low ambient pH in acidified habitat on mechanisms of ionic regulation in gills, which in turn affect the survival and production of juvenile salmon.

Research has also indicated that acidified habitat can affect hormone metabolism and, hence, sexual maturation and reproduction in Atlantic salmon (Freeman *et al.,* 1983; Freeman and Sangalang, 1985; Sangalang and Freeman, 1987; Brown *et al.,* 1990). If the final few months of sexual maturation in freshwater occur in acidified habitat, sex and corticoid hormone metabolism become abnormal. This results in a lack of synchronicity in the peak periods of oocyte maturation and spermiation, which may impair reproduction of the chronically stressed fish. Lower fecundity and higher egg mortality can also result, weight loss can be greater than normal and the fish more lethargic, and the mortality of spawners can be massive in the event of an acidity episode associated with autumn rainfall. These effects on escapement can seriously affect salmon production in river systems where pH levels are low throughout major holding areas during the completion of maturation and before spawning. Such a situation now prevails in Nova Scotia river systems where no salmon have been found in the last two decades. In other acidified river systems, conditions in the main stem and some tributaries are often suitable for sexual maturation and reproduction, thereby allowing some salmon populations to persist.

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The Arctic Ocean: Its role in the global climate engine

E. P. Jones and R. A. Clarke

E. P. Jones and R. A. Clarke

Simulations of the global climate regime under the conditions of the doubling of the concentrations of the radiatively active gases (commonly called a double CO_2 scenario) exhibit global temperature warming ranging from 1°C to 5°C depending on the details of the parameterization of the various atmospheric processes within the models. All models exhibit the largest warming around the periphery of the Arctic and Antarctic ice packs (Hansen et *al.*, 1984; Washington and Meehl, 1986). These climate simulations give a poor representation of present-day sea ice distributions and cycles in the higher latitudes, since sea ice distributions are dominated by ice drift and oceanic processes.

There is a consensus among oceanographers that, while the Arctic Ocean climate will be driven by global changes, the Arctic Ocean itself will not have a major influence on global climate. The climatic changes in the Arctic could be more properly classified as regional and local rather than global. However, given the dramatic changes that global simulations predict will occur in the Arctic regions and the relevance of these changes to large regions of Canada, we must improve our understanding of the Arctic Ocean as a whole in order to predict these regional responses.

The major questions regarding the Arc-

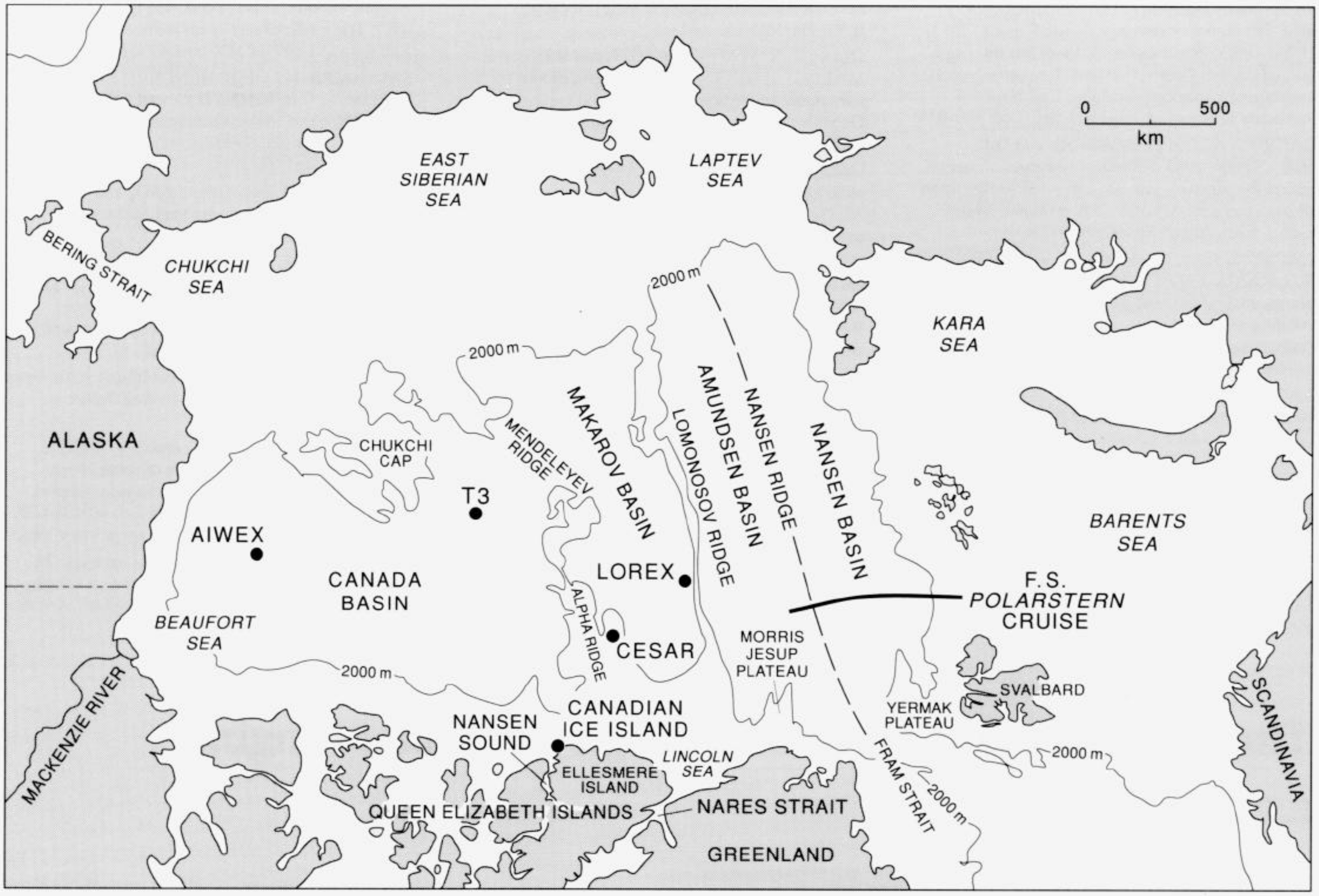

Figure 1. The Arctic Ocean showing ice camps at which modern oceanographic measurements have been made. The historic cruise of F.S. Polarstern *crossed the Nansen Basin approximately along 35° E to 86° N.*

tic Ocean are: What processes contribute to its present cold and dry climate, and how might a changing climate affect these processes? We are just beginning to address the first question and so far can only speculate on the second.

The Arctic Ocean, in contrast to most world oceans, does not have large open borders for the easy exchange of water with the global ocean (Fig. 1). Its main exchange with other oceans is through Fram Strait, where water of Atlantic origin flows in and Arctic Ocean water flows out. In addition, some surface water of Pacific origin enters through the Bering Strait over a very shallow sill, and some Arctic Ocean surface water exits through the Canadian Archipelago.

A second critical characteristic of the Arctic Ocean is its ice cover, which is more or less constant in central regions and seasonal near the coasts. River runoff is particularly significant in the formation of this ice. Without this source of freshwater, the Arctic Ocean ice cover would be much reduced. Ice formation and transport are closely intertwined with heat and salt budgets, which are a major factor in driving ocean circulation and, hence, in determining climate. In an open Arctic Ocean, heat and moisture fluxes, which are now impeded by ice cover, would almost certainly occur on a considerable scale. Ice cover also inhibits wind-mixing of the surface layer and gas exchange, both of which are of potential importance with regard to the removal of radiatively active gases (e.g., carbon dioxide) from the atmosphere.

A third critical characteristic of the Arctic Ocean is its density structure. Freshwater from rivers, and brine production during ice formation over the continental shelves, play a large role in determining the density structure. The continental shelves are unusually large for an ocean basin. They comprise about one-third of the total area of the Arctic Ocean and include pretty well all of the area that undergoes seasonal variation in ice cover. They help to determine many of the characteristics of the Arctic Ocean at all depths and, in fact, may be one of the dominating influences on the whole nature of the Arctic Ocean from the point of view of climate.

The density structure can be described in a general way in terms of four layers (Fig. 2). A shallow (50 m), well-mixed, surface layer of fresher water at the freezing point overlies almost all of the Arctic Ocean. Below the relatively fresh surface layer is a strong salinity (i.e., density) gradient, which means that the water column is very stable. Almost no mixing can occur across such a strong density gradi-

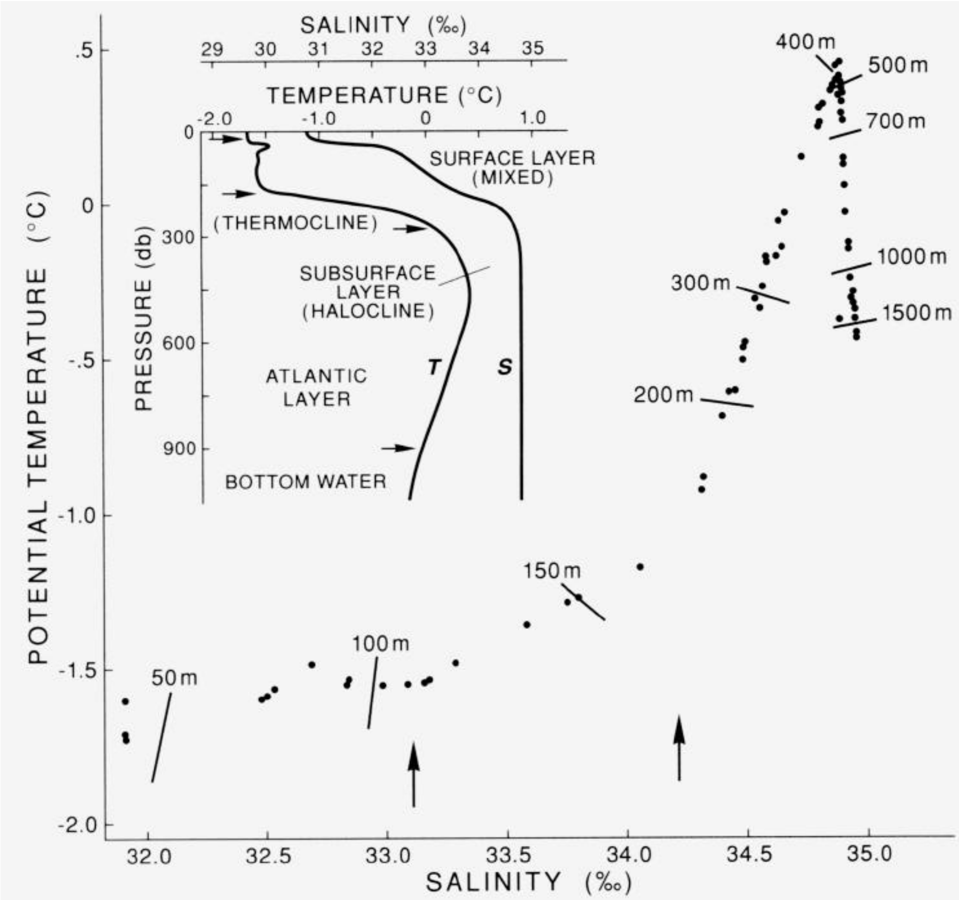

Figure 2. Salinity and temperature profiles and a temperature vs. salinity plot typical of the central Arctic Ocean. The surface layer is characterized by relatively low salinity and near-freezing temperatures. The halocline has a sharp gradient in salinity. The Atlantic layer has a warm core near a depth of 400 m. The deep water has a fairly uniform higher salinity and a lower temperature. The arrows indicate the cores of upper and lower halocline water.

ent, or halocline. There is enough heat in the relatively warm Atlantic layer under the halocline to melt the surface ice, but this water is isolated from the surface by the strong density gradient. The density gradient is in turn maintained to a large degree by considerable freshwater input from large rivers, primarily on the Eurasian side of the Arctic Ocean. Below the Atlantic layer is Arctic Ocean deep water, which is cold but not at freezing temperatures. This rather sluggish water mass (e.g., Anderson *et al.,* 1990) has little exchange with the other oceans and thus plays an insignificant role in global circulation and the transport of heat and salt.

The most active regions of the Arctic Ocean, in terms of determining its water characteristics, are the large Eurasian continental shelves. Here, river runoff and active biological processes during spring and summer contribute to the chemical characteristics of the shelf water, producing signals that can be traced throughout the upper waters of the Arctic Ocean, especially in the halocline (Jones and Anderson, 1986).

The halocline is thought to be maintained by brine rejection during the formation of sea ice (Aagaard *et al.,* 1981; Melling and Lewis, 1982). As ice forms over the shelves, the salt that is rejected produces dense water that flows off the shelves, mixing with and entraining water as it flows into the central regions (Fig. 3). Much of this cold, saline water forms the halocline. Some is dense enough to sink deeper, contributing even to the deepest water in the Arctic Ocean. As water from the shelves flows out into central regions, it carries with it chemical constituents characteristic of a process or a particular shelf region. River runoff contributes dissolved inorganic carbon that can be traced in the surface layer of the Arctic Ocean. The water that maintains the upper halocline receives nutrients regenerated from decayed biogenic matter by biological processes on Asian shelves. Further biological processes on the European shelves reduce the nitrate and oxygen content of this water, which then enters the Arctic Ocean interior as lower halocline water. The water of Atlantic origin is characterized by higher temperatures and salinities.

The characteristics imparted to the upper waters (the surface, halocline, and Atlantic layers - see figure 4) allow them to be traced throughout the Arctic Ocean wherever data have been gathered. Chemical tracers have been extremely helpful in determining the sources of water, especially in the Arctic Ocean where there are few stations. Only a single section has ever been occupied across a central Arctic basin (Anderson *et al.,* 1989), and fewer than half a dozen deep stations from ice camps have ever been occupied in the rest of the central region (e.g., Jones and Anderson, 1986; Jones and Anderson, 1990). Nevertheless, upper waters, from the surface to the Atlantic layer, have been traced to many places throughout the Arctic Ocean and even out through Fram Strait. Of particular relevance to Canada is the fact that the properties imparted to the Eurasian shelf waters are found in the water just off the Canadian coast north of Ellesmere Island, showing that water from the Siberian rivers and the Asian continental shelves is present all the way across the Arctic Ocean and flowing through the Canadian Archipelago (Jones and Anderson, 1990).

In the last century, it was noted that wood from Siberia appeared in northern waters of western Europe. The surface layer circulation has by now been reasonably well documented by tracking ice drift from buoys and various ice camps and stations (e.g., Colony and Thorndike, 1984). We have a moderately good idea of where the water below the surface layer comes from, but we only vaguely know how it moves (e.g., Swift and Koltermann, 1988; Jones and Anderson, 1986; Aagaard *et al.,* 1985; Perkin and Lewis, 1984; Moore *et al.,* 1983). In other oceans, cir-

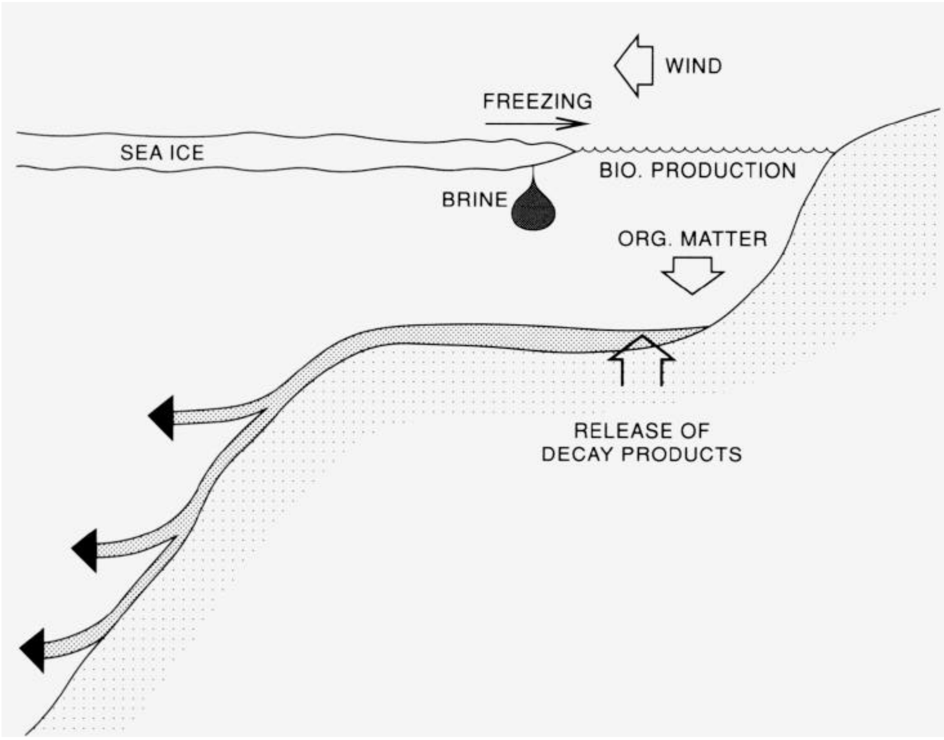

Figure3. A schematic representation of shelf processes producing dense water that advects off the continental shelves into central regions of the Arctic Ocean.

culation is determined by relatively detailed density surveys coupled with arrays of current-meter moorings. The most effective platform for Arctic Ocean oceanography is an icebreaker, which has the facilities to make sophisticated density measurements, together with measurements of various chemical tracers. Current-meter moorings remain a problem because of the difficulty of returning to mooring sites to recover the meters. Deep floats are a new and exciting tool that may be able to overcome the difficulties of recovering current-meter moorings. The floats are carried along by currents at various depths and can be acoustically tracked from the surface by satellite-reporting listening stations set on the ice.

The largest exchange of water between the Arctic Ocean and other oceans occurs through Fram Strait. It has been estimated to be near 5 x 10^6 m^3 s^{-1}, about 5 times greater than all other exchanges. An analysis of data from year-long moorings across the East Greenland current, which were designed to measure the outflow of upper Arctic Ocean water (Foldvik *et al.,* 1988), has resulted in an estimated southward transport in the East Greenland current that is only half the traditional estimates. This is a clear illustration of the tentativeness of our quantitative understanding of the exchange in this region, an understanding that is crucial to obtaining assessments of heat and salt budgets necessary for climate modelling.

Detailed studies of the circulation and the mixing of Atlantic water as it enters the Arctic Ocean through Fram Strait were carried out by Perkin and Lewis (1984). Their data, and other studies within and close to Fram Strait, have shown that there is extensive mixing of the warm salty water with the layers above it as it enters the Arctic Ocean. Some of this heat then goes into the melting of the sea ice as it converges on its exit point through Fram Strait. In addition, much of this water is quickly recirculated southward through Fram Strait. All evidence points to the fact that the circulation regime within and near Fram Strait is extremely complex. Because of the weak density differences among the various waters and the complicated topography, a number of different narrow boundary currents are both possible and likely, some of which may be responsible for the rapid injection of chemical and radioactive transient tracers into the Arctic Ocean (e.g., Smith *et al.,* 1990). It is little wonder that our estimates of the net transports of mass, ice, heat, and freshwater through Fram Strait are so prone to error.

Previously, it had been believed that there was little exchange of the deep waters of the Arctic Ocean with those of the global ocean. Swift and Koltermann (1988) argued on the basis of recent data from Fram Strait and the Norwegian-Greenland Seas that the deep water from the Eurasian Basin of the Arctic Ocean was an important component of the bottom water of the Norwegian Sea. Earlier models of the Arctic Ocean balances had ignored any role of deep-water formation and deep-water exchanges. This assumption will have to be reexamined. It is clear that there is much to learn about the deep-water circulation of the Arctic, and it is likely that geochemical tracers and acoustically tracked deep floats will be the principal tools by which it will be studied over the next decade. The exchanges of the Arctic Ocean with the rest of the global ocean are certainly not yet well established.

The most direct effect of global climate warming would be changes in the surface layer of the Arctic Ocean, which would affect the coupling between the atmosphere and the ocean. The most obvious manifestation would be changes in ice cover. Closely related is the amount of freshwater in the surface layer, now coming largely from river runoff. We have qualitative understanding of how the surface layer is maintained, but we do not have quantitative predictive models for the processes involved. Fairly good ice models can be produced for central regions, but they are poor for marginal ice zones that would include the continental shelves and marginal seas.

Most people would predict a substantial decrease in ice cover as a result of global warming. If freshwater from river runoff decreased as well, the ice cover might all but disappear. Without ice cover, the Arctic Ocean could become more like the Greenland Sea, providing more deep water that could flow into the deep North Atlantic. The Atlantic layer in the Arctic Ocean would seem likely to provide sufficient stability in central regions to prevent deep mixing there, but over the shelves the formation of dense water could be enhanced. A substantial increase in deep-water formation and a more active exchange with

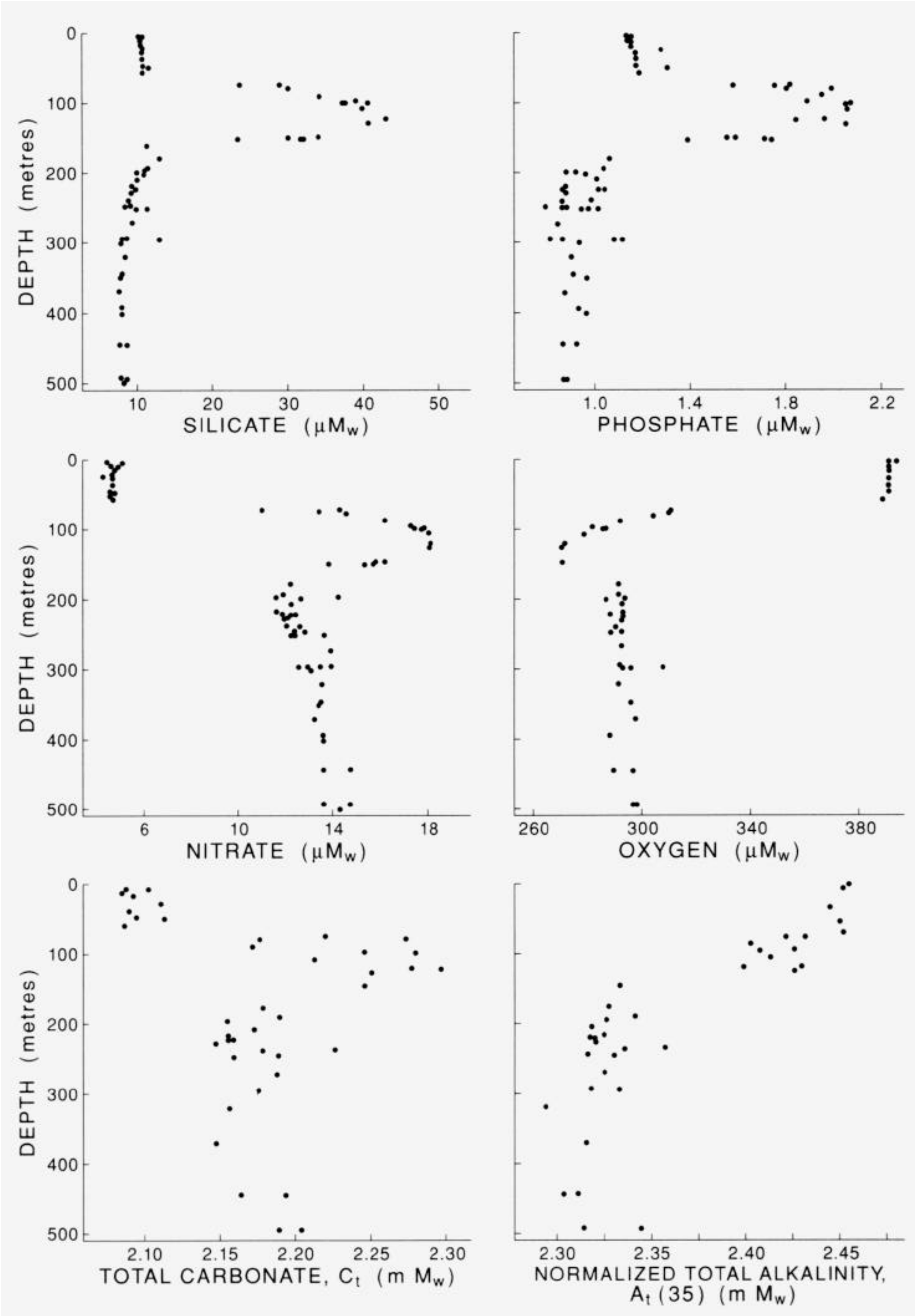

Figure 4. Profiles from the CESAR Ice Camp showing various chemical constituents associated with the various density structures of the central Arctic Ocean. The nutrient maxima (of silicate, phosphate, nitrate, and carbonate) and oxygen minimum are associated with the upper halocline. The normalized total alkalinity shows a river runoff signal in the surface layer.

other oceans would lead to enhanced heat transport from the tropics to the north. Several other climatological effects related to changes in ice cover, including changes in the arctic albedo and evaporation, would impinge on climate. Each change, by itself, could either enhance or diminish climate changes in the Arctic Ocean. It is impossible at this stage to determine climate changes associated with the Arctic Ocean, but it is not far fetched to speculate that there will be regional climate changes and that the Arctic Ocean might play a more significant role in global climate, quite different from the relatively passive role it has now. Before we can predict what changes could occur and the implications of those changes, we must have a much better understanding of how the Arctic Ocean works at present.

Canadian research

The Canadian role in studying these regions has been significant, both in initiating programs and in participating in international programs. Canadian scientists have established several ice camps (LOREX, CESAR, and one on the Canadian Ice Island) and have been part of all the oceanographic expeditions but one on which modern oceanographic measurements have been made. At the latter two camps, programs of the Physical and Chemical Sciences Branch of DFO's Scotia-Fundy Region resulted in many of the general conclusions regarding the origin of the upper-water masses and their circulation patterns within the Arctic Ocean. From this work, it has been possible to conclude that upper water in the central regions which overlies a layer of cooled Atlantic water has components of Siberian river runoff, water of Pacific origin that has been modified on the Siberian continental shelves, and water of mostly Atlantic origin that has been modified much farther to the west on continental shelves north of Europe. An especially significant result from a Canadian perspective is that all of these waters are also clearly identifiable in Canadian waters that lie offshore north of Ellesmere Island and flow through the Canadian Archipelago (Jones and Anderson, 1986; Moore and Smith, 1986; Jones and Anderson, 1990).

Oceanographers at BIO also took part in international expeditions onboard the modem German icebreaker F.S. *Polarstern* on its recent historic cruise across the Nansen Basin in the Arctic Ocean (Anderson *et al.*, 1989), and they will participate in what is expected to be another pioneering joint cruise of the Swedish icebreaker *Oden* and the F.S. *Polarstern* to obtain data from sections in three Arctic Ocean basins. Preliminary ideas regarding a five-year comprehensive program to study the Arctic Ocean are presently being circulated among the Canadian oceanographic community. The development of models that adequately describe the present ocean and that can be used to help predict future regional climate changes must become a high priority. With our past and present involvement in Arctic Ocean research and with our obvious interest in our northern climate, there is every good reason to hope for and expect significant Canadian contributions to future Arctic Ocean research.

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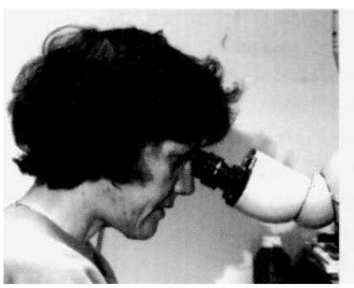
Canadian Ice Island: Environmental studies of the polar margin north of Canada's arctic islands

P. J. Mudie, K. Ellis, and B. T. Hargrave



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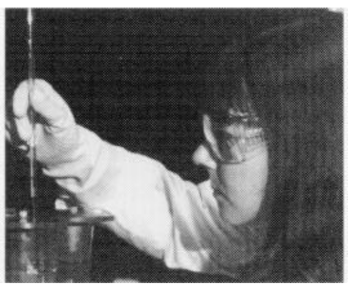

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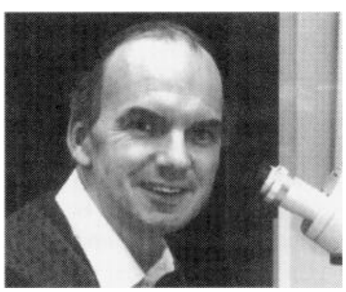

B. T. Hargrave

Studies of the Arctic Ocean's tectonic origin, oceanography, and climatic history have long been identified as major needs of marine research. More recently, knowledge of arctic climate, ice dynamics, and the sources and pathways of contaminants to biotic communities have been targeted as research goals for the International Geosphere-Biosphere Program. The perennial sea-ice cover, extending from the North Pole to Greenland and along the Canadian polar margin, has previously restricted most studies to the warmer marginal seas (e.g., Fram Strait, and the Beaufort, Bering, and Barents seas) where seasonal ice can be navigated in summer (Fig. 1). Until recently, little or no data have been available for the pack-ice-covered continental shelf north of the Canadian arctic islands, which comprises about 20% of the Arctic Ocean margin and which includes the coldest, driest part of the High Arctic.

The occupation of a field station on the Canadian Ice Island since 1984 has allowed the collection of a unique set of new scientific data for this previously unknown polar region. From 1985 to 1989, investigations by laboratories built on the Ice Island by DEMR and DFO staff from BIO have provided new insights into the fol-

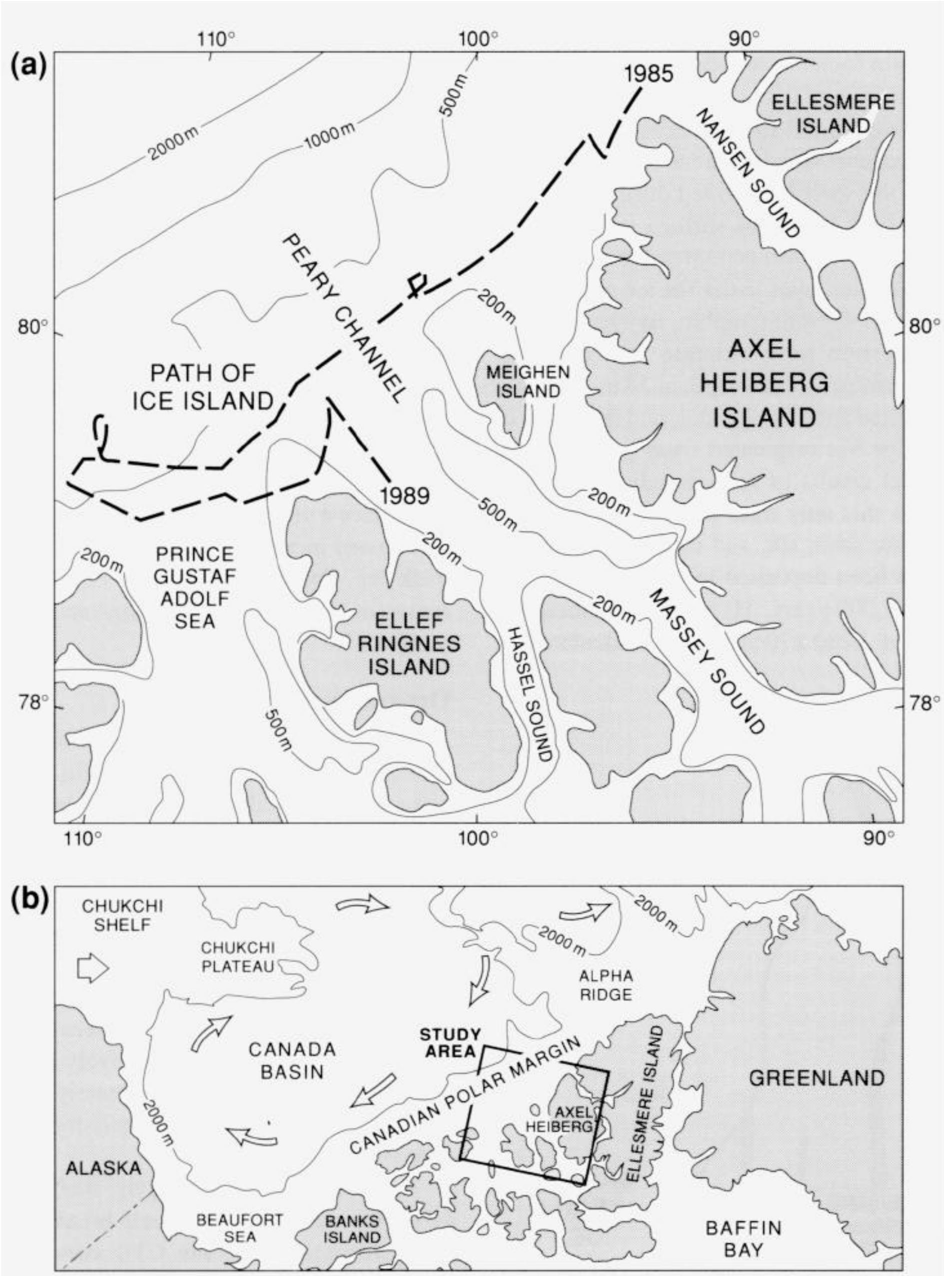

Figure 1. (a) Drift track of Canada's Ice Island from 1985 to 1989. (b) The Arctic Ocean, showing major ocean basins and continental shelves, the Beaufort Gyre Current (see white arrows), and the location of the Ice Island study area on the Canadian polar margin.

lowing areas of environmental marine science: the genesis and dynamics of arctic sea ice; sediment processes and the cycling of particulate organic carbon under the high arctic pack-ice margin; the Quaternary and recent history of sea-ice cover and climate change; the oceanographic, geochemical, and biological processes that govern sediment transport and deposition; and the cycling of atmospherically derived radiochemical and organic pollutants within the marine environment and Arctic Ocean biota.

Field methods

Ice islands are rare features of the Arctic Ocean ice cover, a few being formed each decade when tabular icebergs are calved from floating ice shelves on the north coast of Ellesmere Island. The ice islands are several km long and up to 50 m thick. They usually encircle the western Arctic Ocean for 5 to 30 years before drifting south through Fram Strait or the inter-island channels (Fig. 1). The large size, stability, and longevity of arctic ice islands make them useful floating platforms for geological and oceanographic research in areas of the western Arctic Ocean where perennial sea ice, up to 7 m thick, prevents access by ships.

In April 1983, several newly calved ice islands were found near the Ward Hunt Ice Shelf off northwest Ellesmere Island. In September 1984, funding from the Canadian Frontier Geoscience Program, in collaboration with the Department of Energy, Mines and Resources, the Department of Fisheries and Oceans, and the Atmospheric Environment Service, enabled the Polar Continental Shelf Project (PCSP) to start building research facilities on one of these ice islands for geological, geophysical, meteorological, and oceanographic studies of the continental margin north of the Canadian Arctic Archipelago. The field camp can now support 35 people in 14 wooden buildings and 6 large, insulated tents. A camp generator provides up to 50 kW of power. Support facilities include a mechanical workshop and an electronics workshop. Scientific facilities include a SATNAV navigation system, a seismic reflection array, an explosives magazine, and an instrument hut. A geology laboratory with a small dry-lab area for chemistry houses 7-tonne and l-tonne winches and a 50 kW power supply to run them. In addition, it holds a hot-water boiler system, which is used to melt a hydrohole (1.3 by 1.3 m wide) through 44 m of ice below a gantry 8 m high (Gorveatt and Chin-Yee, 1988). The heat-exchange system is also used to melt holes for oceanographic work carried out near the geology laboratory.

Ice Island structure and dynamics

The Canadian Ice Island is elliptical in shape, with an area of about 26 km^2, a mass of about 700 by 10^6 tonnes, and a maximum thickness of 45 m. Aerial observations, aerial photographs, and airborne radar imagery show that, at the time of calving, the island comprised two types of ice: a core consisting of approximately 16.5 km^2 (64% of the area) of shelf ice about 42.5 m thick, and old multiyear landfast ice (Fig. 2). The multiyear landfast ice is about 10 m thick and was previously attached to the front of the Ward Hunt Ice Shelf. Since calving, an area of about 5 km^2 of multiyear pack ice has also become attached to the opposite side of the shelf-ice core. The surface topography of ridges and troughs, termed "rolls", is characteristic of all ice islands. Runoff from snow meltwater collects in depressions and forms lakes during the brief summer melt period in August.

Four ice cores have been drilled in the Ice Island and analyses were undertaken to determine its growth history. Measurements were primarily taken of the specific electrolytic conductivity (SEC) of the ice, the amount of oxygen-18 deuterium, and tritium it contains, and its density; crystallography was also performed. Bulk samples from one core are being studied for sediment and pollen-spore content and for diatom composition. Initial results show that the entire thickness of the Ice Island core is composed of granular, nonsaline ice of freshwater origin, with a mean density of 872 kg/m^3 (Jeffries *et al.*, 1988a, b). High levels of anthropogenic tritium found in the ice at a depth of 37 to 42 m suggest that the bottom ice has accreted since 1963. Previous data from the eastern Ward Hunt Ice Shelf suggested that the shelf ice formed during a 400- to 500-year period of surface ice loss, balanced by bottom accretion from a surface freshwater layer under the ice shelf. New data on crystallographic, oxygen-18, and deuterium now indicate that only the lowermost ice (at a depth of 28 to 30 m) has accreted from freshwater, and that most of the ice has originated from precipitation. Initial results of the ice-sediment studies show that only trace amounts (<0.1 g/m^2) of fine sand, silt, and clay-sized particles have been deposited in the ice during the past 2,000 years. However, a radiocarbon age of 2,280 ±70 years B.P., calculated on organic matter found in cryoconite holes on a ridge near the Ward Hunt multiyear ice, suggests that there are periodic large influxes of aeolian or morainal sediment, as also indicated by drop stones found on the seabed and in sediment cores (Mudie *et al.*, 1986). During the exceptionally warm summer of 1988 (2 to 4°C above normal), massive blooms of brown ice algae were observed on the Ice Island and on sea ice between Meighen and Ellef Ringnes islands. These patches of dark brown algae resemble particle-laden ice that is common in multiyear ice of the Transpolar Drift (Pfirman *et al.*, 1989). These brown ice algae have a similar effect on reducing the albedo and increasing melting rates of the pack ice, despite the paucity of elastic sediment in the ice on the Canadian polar margin.

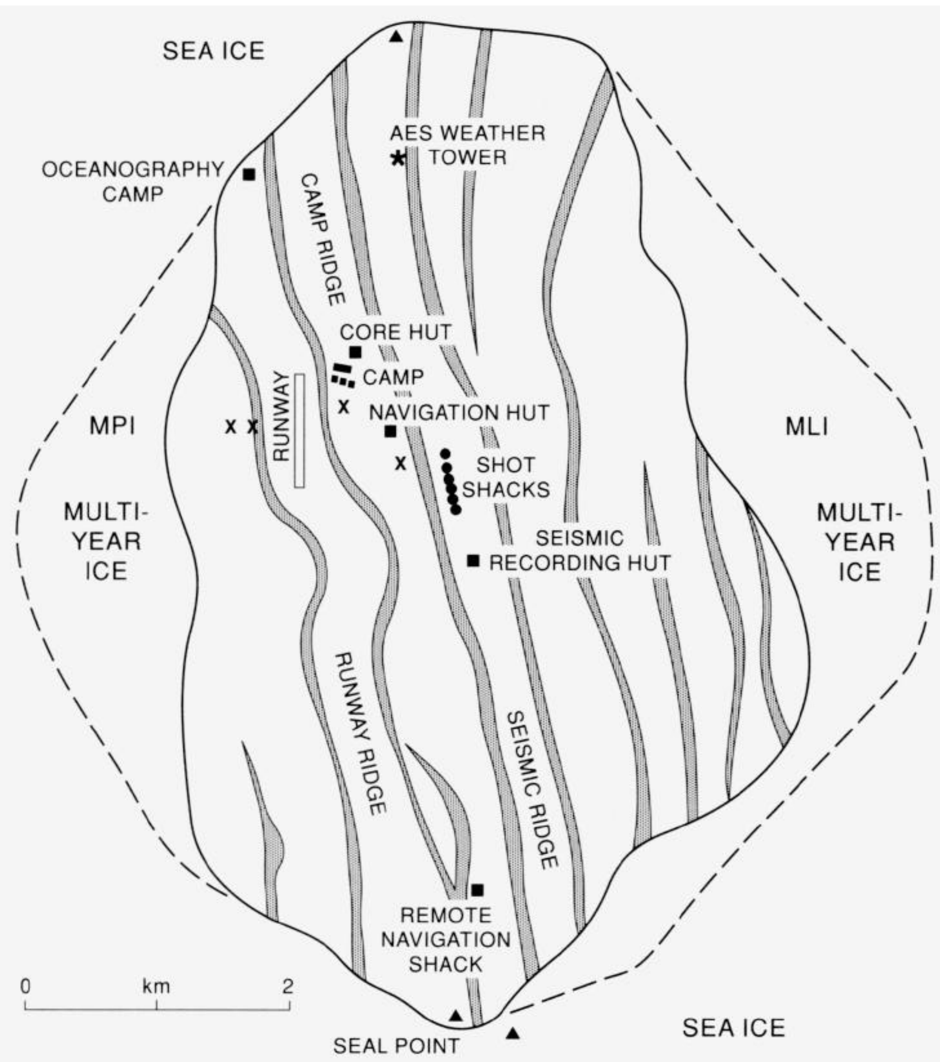

Figure 2. The major physiographic features, main camp facilities, and areas of muddy ice on the Canadian Ice Island. Ice cores were taken from the ridge between the navigation hut and shot shacks. ML1 = multiyear landfast ice; MPI = multiyear pack ice.

Oceanography

The nature of water movement on the Canadian polar margin is uncertain on a large scale and unknown in many details. Physical oceanographic data were collected by helicopter-operated through-ice CTD surveys conducted during the springs of 1986, 1988, and 1989. The results show that the waters over the continental shelf northwest of Axe1 Heiberg Island are significantly different from waters over Canada Basin, despite the relatively great shelf depth (average approximately 400 m) and the lack of strong shelf-forcing processes.

A frontal zone separating the shelf and offshore regimes at the shelf break has been delineated by the CTD surveys. Strong current shears penetrating to below 800 m have been measured at this front, indicating the presence of a narrow shelf-break current. Other evidence for a shelf-break current comes from the presence of coarse, winnowed sediments at the top of cores taken from the shelf break. Further study of this feature is planned by the Frozen Ocean Lab of the Institute of Ocean Science (IOS), which will use neutral-buoyancy floats to track the water movement acoustically.

An arctic current meter has been deployed successfully by fixing it relative to geographic north through the use of 48 m of aluminum extension rods in the marine geology hydrohole (Mosher *et al.*, 1988). Records for the meltwater layer were ob-

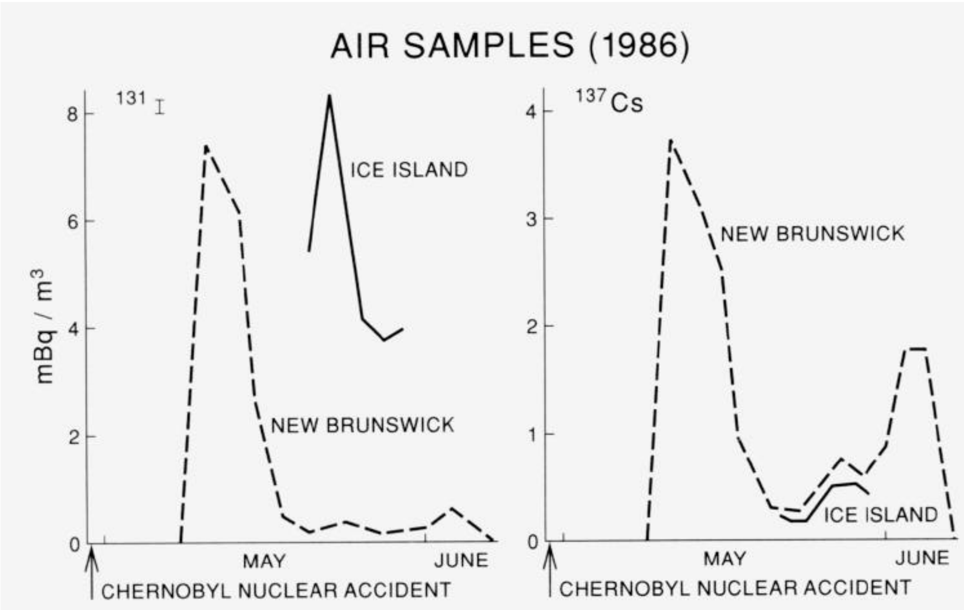

Figure 3. Comparison of levels of ^{131}I and ^{137}Cs in air on the Ice Island and in eastern Canada after the Chernobyl nuclear accident on May 16, 1986.

tained for 24-hour periods in 1988. These data showed large seasonal differences. In the spring's closed pack ice, only very small, random oscillations were evident; in early summer, when large leads were open near the Ice Island, significant semidiurnal oscillations were recorded.

Chemical oceanography is being studied from water-bottle casts made through the Ice Island hydroholes and from a remote camp on the shelf break north of Ellef Ringnes Island. Characterization of arctic surface and Atlantic water layers is being achieved by measuring the organic content in suspended particulate matter, the stable isotopes in the organic matter, the dissolved inorganic carbon, the dissolved oxygen, the stable isotopes of the water (Macko *et al.*, 1986), the radioactive nuclides of ^{137}Cs, ^{90}Sr, $^{210}Pb/^{210}Po$, ^{226}Ra, and $^{239,240}Pu$, and the tritium, freons, and inert gases such as krypton and argon (Moore and Wallace, 1988). Salient initial results indicate that rates of carbon use under the pack ice on the Canadian margin are among the lowest for the world's oceans, and that nitrogen isotopic enrichment in the microbiota and plankton is extraordinarily high (Pomeroy *et al.*, 1989).

Until recently, ^{137}Cs entered the Arctic Ocean exclusively through nuclear weapons tests, but these sources are now augmented by those from the Sellafield nuclear reprocessing plant and the Chernobyl nuclear accident in April 1986. The detection of several isotopes, such as ^{137}Cs and ^{131}I, which were released during the Chernobyl accident and found on air particulate-matter samples collected at the Ice Island during May 19-31, 1986 (Fig. 3), confirms the atmospheric contributions that Chernobyl has made to the Arctic Ocean. The high levels of ^{131}I as compared to those in eastern Canada (Smith and Ellis, 1990) for the same period illustrate the important role of the atmosphere in the direct transport of industrial pollutants from Europe to the Arctic.

The three sources of ^{137}Cs have been traced through the Arctic Ocean using a lateral transport-box model to study the movement of pollutants and to determine rates of ventilation of the water column. Models of the profiles measured at the Ice Island (Fig. 4) in Peary Channel (1989) and northwest of Axe1 Heiberg Island (1985 and 1986) show similar ventilation ages. Comparison with profiles from the central Arctic Ocean at the Canadian Expedition to Study Alpha Ridge (CESAR) (Smith and Ellis, 1990) indicate a longer time scale for halocline ventilation on the Canadian continental shelf than in the central Arctic Ocean. At present, initial inert gas measurements support the model of Moore and Wallace (1988), which shows that the temperature of the arctic surface water may be governed by the transfer of heat directly to the sea ice. This model has important implications for studies of ocean-atmosphere heat transfer in the Arctic Ocean and for the ventilation of the deep basins.

Particle-reactive $^{239,240}Pu$, ^{210}Po, and ^{210}Pb are used to study scavenging rates. The low ^{210}Pb and ^{210}Po activities in the central Arctic Ocean (Moore and Smith, 1986), in the presence of high activities of parent ^{226}Ra, indicate very effective particle-scavenging within the nutrient maxima

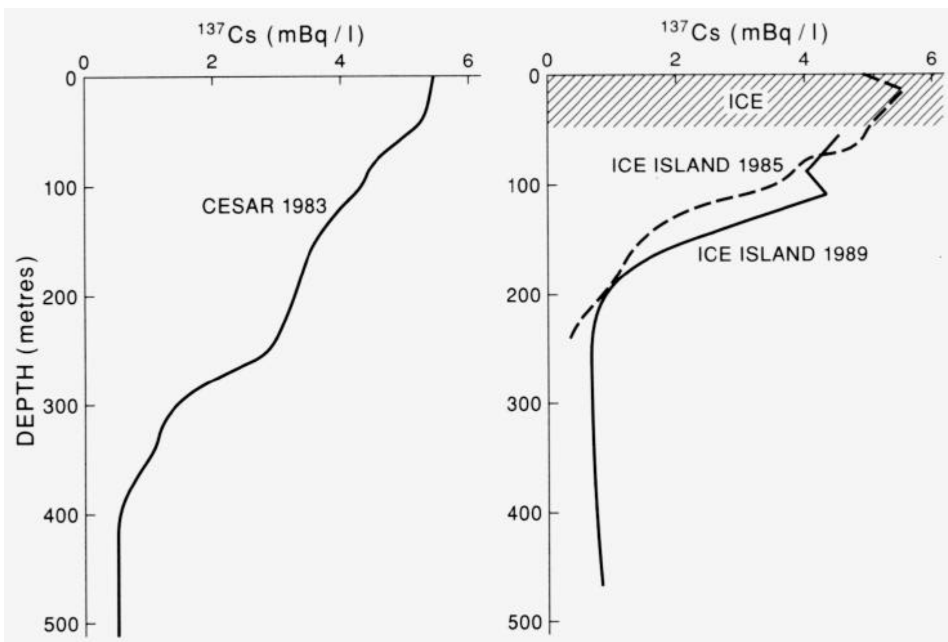

Figure 4. Distribution of ^{137}Cs in water of the central Arctic Ocean (CESAR) and under the Ice Island.

near the boundary of the arctic and the Atlantic water layers. A similar but less dramatic decrease observed for ^{210}Po collected in 1989 in Peary Channel suggests that less-pronounced scavenging occurs over the Canadian continental shelf.

The profile of $^{239,240}Pu$ measured in Peary Channel in 1989 is one of only two profiles reported for the western Arctic Ocean. The measured $^{239,240}Pu/^{137}Cs$ ratios above 200 m are lower than the expected fallout ratio of 0.0213, suggesting very efficient removal of plutonium from surface layers by particle scavenging, although the mechanisms are not presently known. The low activities of ^{210}Pb and ^{137}Cs in sediment cores collected from the Ice Island in 1988 and 1989 (Fig. 5) are indicative of low atmospheric deposition of ^{210}Pb in the arctic region and low sediment accumulation rates. Areas of potentially high accumulation rates have been identified for future core collection on the basis of ^{210}Pb analysis of grab samples collected during helicopter surveys in 1989.

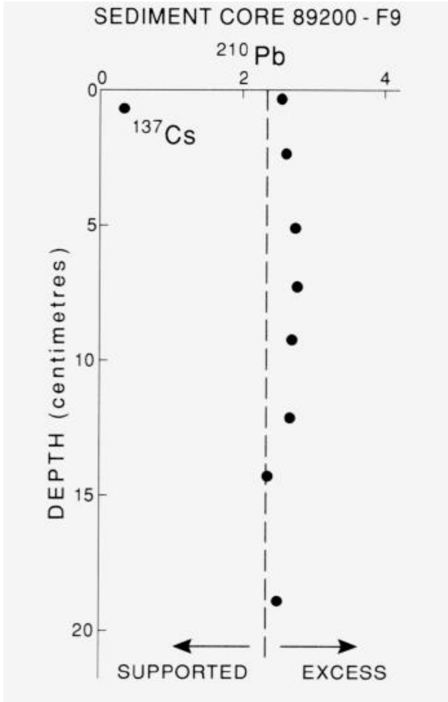

Figure 5. Profile of excess ^{210}Pb in core 89200-F9 from Peary Channel.

Vertical fluxes of particulate matter

A multi-cup sediment trap was suspended at a depth of 100 m under the Ice Island from September 1986 to April 1987. The drift track of the island during this period (Fig. 1) was along the continental margin off Axe1 Heiberg Island. Annual particulate-matter sedimentation, measured as total weight, organic carbon, and nitrogen, is the lowest recorded for any world ocean region (Hargrave et al., 1989). This is expected, since the Arctic Ocean is known to be the least productive in the world. Estimated annual values are an order of magnitude lower than those predicted from global carbon budgets. The correspondingly low concentrations of suspended particulate matter in the water column under the Ice Island in its present location over the Canadian continental shelf probably explain the low rates of scavenging of radionuclides mentioned above.

The low sedimentation rates measured between 1986 and 1987 were not uniform throughout the collection period. Surprisingly, the highest rates of total mass flux in January and of particulate organic carbon and nitrogen during February to March occurred during the dark winter period, when the production of organic matter by phytoplankton and under-ice (epontic) algae should be minimal. The presence of cells in settled material collected in the trap indicated that blooms of diatoms (mostly *Melosira arctica)* occurred during summer periods of continuous light, as well as during the winter dark season. Water-column plankton tows conducted during August 1986 showed that blooms of the brackish-water dinoflagellate *Peridiniella catenata* also occurred.

Two sediment traps containing a total of 35 cups were deployed from the Ice Island in September 1989 for retrieval one year later. A more frequent sampling interval (2 to 4 weeks over 12 months) will allow greater seasonal resolution of variations in the settling of particles through the water column and will provide better resolution of seasonal changes in the vertical transport of settling particulate matter through the water column.

Transfer of atmospherically transported organic contaminants to the Arctic Ocean food web

The Canadian Ice Island has been used as a sampling platform to compile an inventory of chlorine-containing hydrocarbon contaminants (organochlorines) present in the atmosphere, snow, sea ice, water, sediments, and marine organisms captured under the ice in the Arctic Ocean. There are various routes by which these man-made pesticides and industrial compounds enter this ocean: from atmospheric sources (rain, snow, and particle fallout) and rivers, and through water exchange with the North Atlantic and Pacific oceans.

The atmosphere is probably the major route by which semivolatile organochlorines are supplied to the Arctic Ocean. These compounds vaporize following application as pesticides in agricultural and urban areas in southern latitudes. They may also be released by municipal and industrial incinerators. The presence of similar organochlorines in various parts of the arctic environment shows how effective atmospheric transport has been in their global distribution (Hargrave *et al.,* 1988). This could explain how native people in northern Canada accumulate these chemicals through their diet when no local sources exist. However, prior to 1986 no measurements had been made in offshore areas of the Arctic Ocean. Data collected to determine the presence of organochlorines in air, snow, seawater, and biota provide the first quantitative measurements of these compounds in offshore areas of Canada's northern coast. The baseline information can be used to detect long-term trends in changes in their concentrations in the Arctic Ocean.

The most abundant chlorinated hydrocarbons in the air, snow, and water under the Ice Island are isomers of hexachlorocyclohexane (HCH) and hexachlorobenzene (HCB). These water-soluble pesticides enter the water column through vapour exchange and wet and dry fallout of particles. Surface water layers (those in the upper 60 m), identified by their characteristic temperature, salinity, and concentrations of dissolved nutrients, contain the highest concentrations of HCHs and HCB (Fig. 6). The profiles indicate that these contaminants in surface water layers are probably derived by transfer from the atmosphere through runoff of snow meltwater or by direct vapour exchange across open water regions. Lower concentrations in water more than 200 m deep reflect water exchange with the deep North Atlantic Ocean.

Biological sampling to collect biota from the Ice Island has involved the use of plankton nets and baited traps set on the bottom to attract scavenging crustaceans. Analyses of plankton, suspended particulate matter, and organisms such as benthic amphipods (Fig. 7) show that less water-soluble pesticides such as DDT and PCBs are concentrated by factors of 10 to 1,000 times over levels present in water. Chlorinated compounds that are present in the lowest concentration in the air and dissolved in sea water are those that are most abundant in the ocean biota because of their affinity for lipids. Although the concentrations are generally among the lowest values measured within ranges for marine plankton from more southern latitudes, relatively high (in terms of µg/g lipid, or ppm) levels of DDT and chlordane compounds, PCBs, and toxaphene (such as polychlorinated camphenes and PCCs) are present in planktonic and benthic crustaceans. The same compounds are present in fish liver samples at equivalent or slightly lower levels. Neither DDT nor PCCs have been found in air samples previously collected at such high latitudes. Long-distance transport from Siberia and Asia appear to be the most likely sources. Further studies are needed to determine if concentrations of organochlorines in biota show trends over time. If the Ice Island drifts into other areas of the Arctic Ocean, studies can be carried out to compare concentrations regionally.

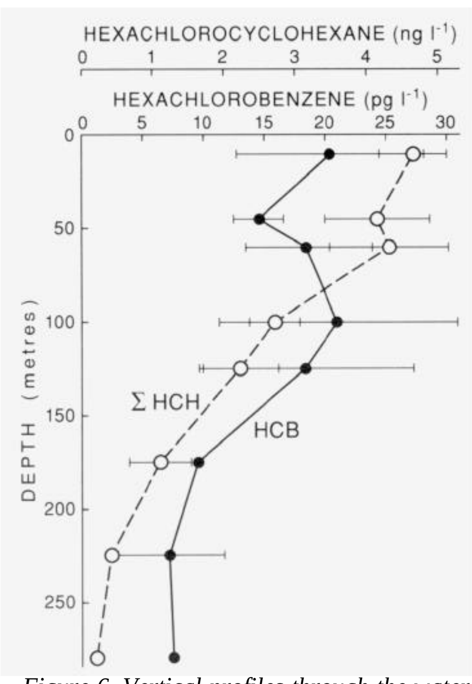

Figure 6. Vertical profiles through the water column under the Ice Island (1986-87) showing dissolved (<1 mm) concentrations as means (symbols) and one standard deviation (horizontal bars) (n = 3 to 6) for the two most abundant organochlorine compounds present in seawater (from Hargrave et al., 1988).

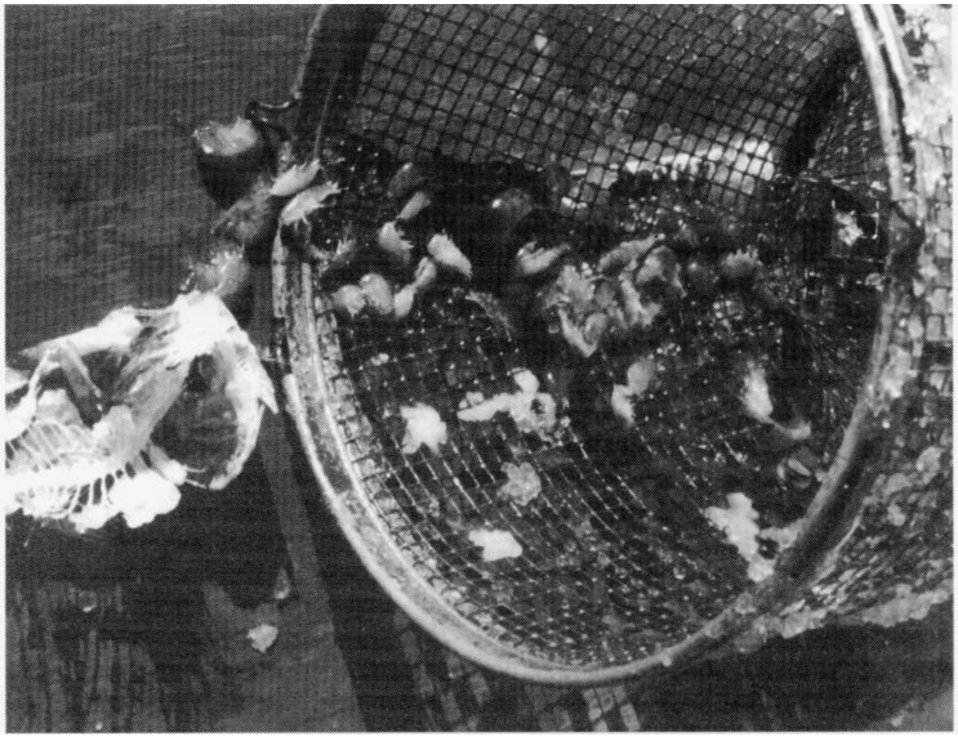

Figure 7. Baited traps, exposed on the bottom for only a few hours when the Ice Island is not drifting, attract numerous scavenging amphipods such as Tmetonyx cicada. *These and other smaller organisms concentrate organochlorine pesticides and PCBs from seawater and suspended particulate matter. The contaminants are transported to the ice surface in snow, dust, and vapour. The marine food web is thus directly linked to the atmospheric transport of these industrial contaminants.*

Environmental marine geology

From 1985 to the present, surficial sediments and benthic biota on the Canadian polar margin have been sampled and mapped in spring and summer, using the Ice Island as a permanent field camp for continuous 12 kHz bathymetric surveys, shallow high-resolution (3.5 kHz) seismic profiling, seabed photography, grab and dredge sampling, and coring by means of Benthos gravity corers or piston corers lowered through the hydrohole. Since 1987, regional sampling coverage has been extended each spring by helicopter flights across the polar margin, with samples of the seabed taken from holes melted through frozen leads in the pack ice.

Initial results include the following important new findings: (1) Five late-Quaternary sediment facies are widely correlatable over depths of 120 to 300 m on the inner shelf, but the outer shelf and slope to 1,200 m have only a veneer (<10 cm) of postglacial Holocene calcareous mud overlying massive ice-rafted siliclastic deposits of probable late-Wisconsinan age (Hein *et al.*, 1990). (2) Lithofacies, benthic and planktic foraminifera, pteropods, and palynomorphs reflect fluctuations in ice cover over a full glacial ocean, and variations in the amounts of ice-rafted detritus deposited during the postglacial (< about 7,000 years B.P.) Holocene interval. (3) There is no clear evidence from either sedimentology or geotechnical properties to indicate the presence of grounded continental ice on the shelf during the last glacial cycle. (4) However, synsedimentary fault structures in cores from a bedrock ridge suggest recent isostatic adjustment to ice loading or tectonism on this unusually deep polar margin. (5) A unique High Arctic calcareous benthic and siliceous fauna lives under the perennial ice and characterizes the late Holocene sediments; this fauna appears adapted to very slow average rates of organic and inorganic sediment influx (2.2 g/m^2/year) with sporadic higher influxes of ice-rafted detritus to yield an average sedimentation rate of approximately 1 cm/1,000 years. (6) Siliceous demosponges *(Geodia sp. cf. G. phlegraei)* form reef mounds on the inner continental shelf and they show a clear depth zonation (Fig. 8), which suggests that there has been a relative sea-level rise, or a shift in the pycnocline, of 20 to 60 m during the last 400 to 1,000 years (Van Wagoner et *al.*, 1989). These biota also play an important role in trapping and stabilizing the fine-grained ice-rafted sediment on the High Arctic polar margin.

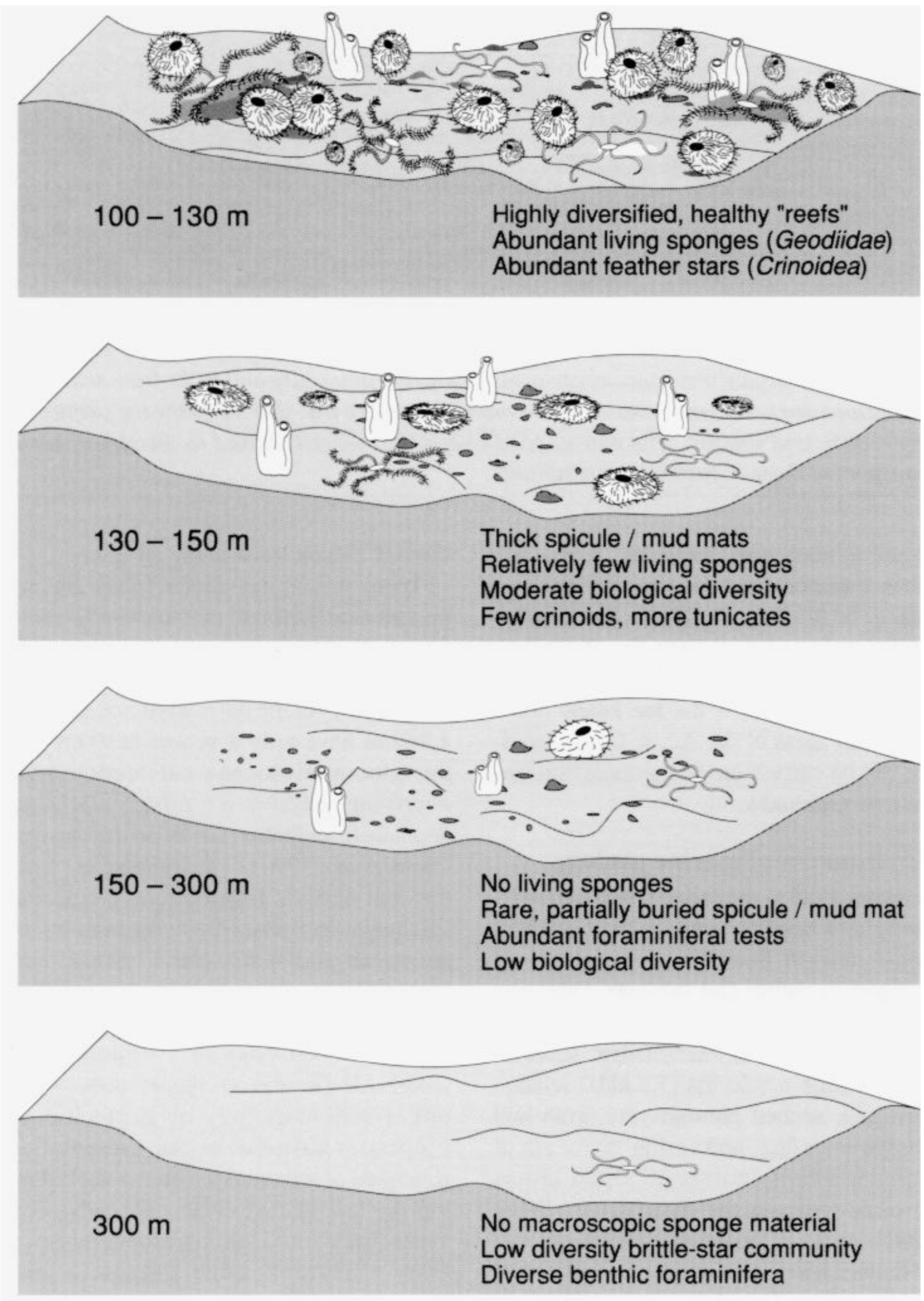

Figure 8. Depth zonation of arctic sponge reefs north of Axel Heiberg Island.

Conclusion

The Canadian Ice Island has proved to be a valuable stable platform from which a broad spectrum of scientific studies can be carried out to provide new data on a previously unknown part of the Arctic Ocean. The Ice Island is now located in Peary Channel at a water depth of about 500 m, and it is hoped that it will move north into the Beaufort Gyre after the spring channel-ice breakup. However, even if the island remains in the channel, it will continue to be valuable as the only field lab from which large, heavy equipment can be deployed in those northernmost Canadian waters that cannot be reached by Canadian icebreakers. Plans for additional work include the testing of small ROVs for sounder profiling and photography of the seabed. Several small-scale drilling systems, a Mesotech sidescan sonar system, and other mapping tools that can be installed on a Class 8 Canadian icebreaker could also be tested from the Ice Island.

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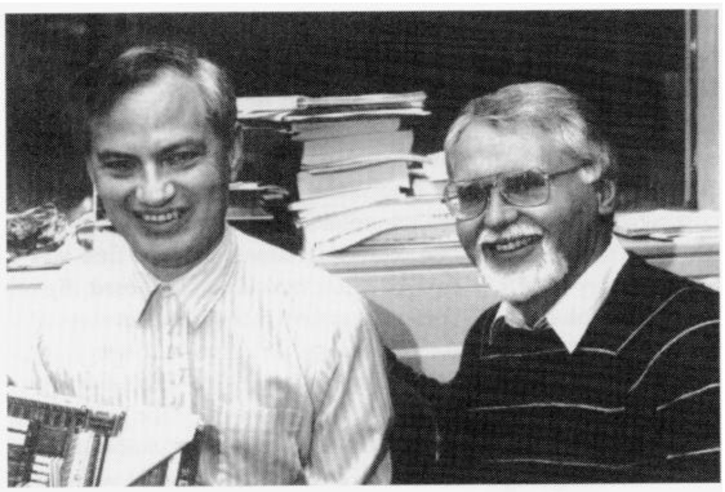
Research in hydroacoustics

N. A. Cochrane and D. Sameoto



N. A. Cochrane and D. Sameoto

During the 1950s and '60s high-frequency echosounding systems revealed reflecting layers and isolated targets of biological origin. By the late 1970s BIO programs in both fish and zooplankton acoustic detection were initiated. Miniaturization of electronics, the widespread use of digital techniques, and advances in theoretical interpretation have put hydroacoustic assessment into a phase of rapid growth. Acoustic detection techniques have the ability to produce a nonintrusive two-dimensional view of biological scatterers with a rapidity and spatial resolution impossible with traditional nets or other forms of "point" sampling. The initial enthusiasm that is generated by employing acoustics is often tempered when the difficulty of identifying specific properties of the resolved biology is recognized. Yet this problem is not intractable, and the goal of acoustics serving as a fast, simple, and quantitative tool for routine biological surveying and mapping is realistic and achievable.

Before treating BIO's zooplankton acoustic program, let us consider some basic principles. Hydroacoustic assessment utilizes sophisticated underwater echosounding systems. Acoustic waves, consisting of a short burst or sound pulse of a given acoustic frequency or wavelength, are sent out from a transducer. The pulse travels through the water, often for a considerable distance, until it encounters an object whose acoustic properties contrast with those of the water. In this case, a portion of the acoustic signal is scattered or reradiated, and some of it returns to the original transducer - now acting as a receiver. The returned signal is recorded and quantitatively analyzed.

The relative strength of the "backscattered" signal, after corrections have been applied to remove signal propagation losses, depends on the contrast between the physical properties of the scattering organism and sea water, on the dimensions and orientation of the organism, and on the ratio of these dimensions to the acoustic wavelength. Theory shows a zooplankter to scatter sound efficiently and with only slight acoustic wavelength dependence for wavelengths less than the spatial dimensions of the zooplankter's equivalent spherical volume (geometric scattering). At longer wavelengths, backscattering levels decrease rapidly (Rayleigh scattering), and the scatterers, unless very numerous, quickly become undetectable. In general terms, obtaining size information depends on observation of the Rayleigh to geometric transition wavelength or corresponding acoustic frequency. When observations of backscattering signal strengths over a wide range of different frequencies are interpreted by scattering theory, one should be able to determine the size/abundance properties of a single-size or even mixed-size zooplankton population. This is a difficult task, both analytically and in terms of the complex instrumentation required.

A practical consequence of the above considerations is that a given echosounder will "see" organisms only down to a certain cutoff size, determined by the instrument's operational frequency (higher frequencies see smaller organisms). Frequencies of 50 kHz to 1 MHz should be the most useful for observing zooplankton that range in length from a few cms (euphausiids and shrimp) to about 1 mm (small copepods). A serious constraint is that the absorption of sound in sea water increases very rapidly with frequencies above 50 kHz. To detect zooplankton to maximum continental-shelf depths of 300 m, sonar systems operating above 200 kHz must be deep-towed in proximity to their targets, a challenging technical requirement.

In 1970, a Simrad 120 kHz echosounder was purchased by BIO's Marine Ecology Laboratory (MEL). In three cruises spanning 1972-74, this sounder was used to map diurnally migrating euphausiid layers in the Gulf of St. Lawrence and the St. Lawrence estuary. Promising correlations between zooplankton abundances, estimated from paper echograms and Bongo net samples, and primary productivity, estimated from chlorophyll measurements, were noted (Sameoto, 1976). However, the need for a quantitative acoustic data-logging system to allow sophisticated computer postprocessing, and for a more versatile and efficient net system, were evident. These problems were partially addressed by the mid-70s through the addition of an analog instrumentation tape recorder for the acoustics, which permitted postcruise digitization, and by the development of the remotely controlled ten-net BIONESS (Bedford Institute of Oceanography Net and Environmental Sensing System) sampler (Fig. 1). Laboratory and theoretical studies published in the late 1970s showed sound scattered from elongate shrimp-shaped organisms like euphausiids to be very dependent on their orientation. Cameras mounted on BIONESS during cruises in the Gulf in 1976 and '77 showed natural euphausiid orientations to become more random during hours of darkness, thereby significantly reducing acoustic target strengths (Sameoto, 1980).

In 1977, '78, and '79, acoustic and BIONESS sampling was extended to the outer Scotian Shelf Break and Rise. Again, strongly diurnal patterns were noted by both acoustics and BIONESS. However, the biological community had many components and was much more complex than that in the Gulf (Sameoto, 1982). It was becoming clear that, to reliably interpret the acoustics, it would be necessary to use multiple frequencies in order to separate acoustic populations by size. At the same time, BIO physical oceanographers were becoming interested in using acoustic backscattering to delineate internal waves and turbulent mixing associated with tidal flows at the edge of the Scotian Shelf. A consequent acoustic effort in the Metrology Division of the Atlantic Oceanographic Laboratory (AOL) saw common ground with the biological efforts and combined forces. In 1981, two dual-channel Datasonics precision gain-controlled echosounders were acquired between MEL and AOL to replace the less-accurate Simrad sounder. With ongoing modifications, the Datasonics sounders have served as the nucleus of our field instrumentation to the present.

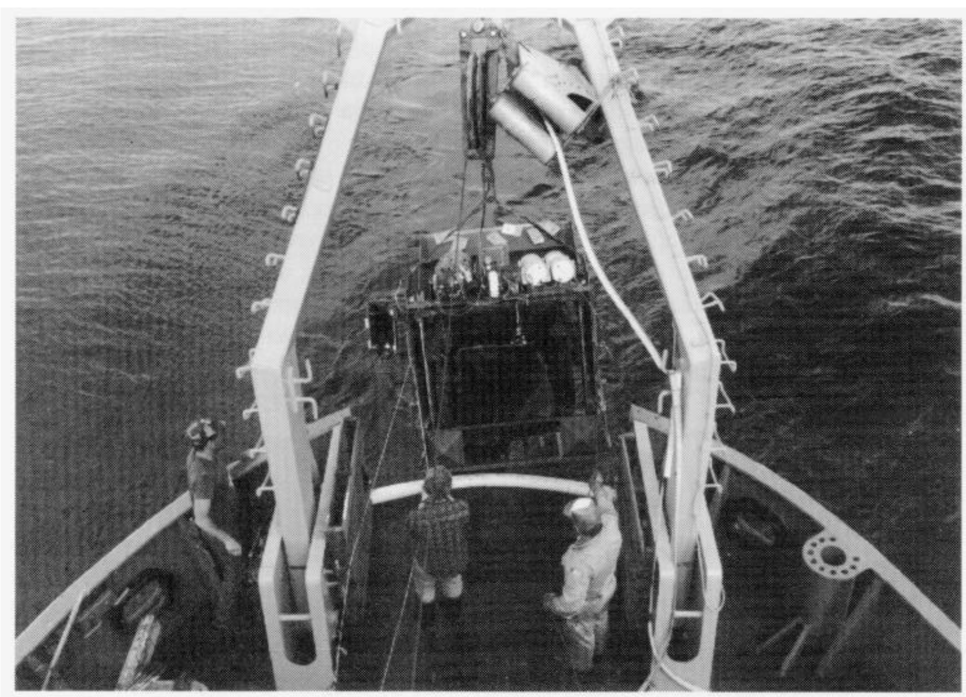


Figure 1. The ten-net BIONESS sampler. Nets are released by command from the surface, allowing zooplankton sampling over selected depth ranges.

In May 1983 a study was undertaken of the response of nighttime scatterers to artificial surface lights in Emerald Basin (Sameoto *et al.,* 1985). Turning on a powerful downward-directed quartz halogen lamp produced a dramatic and virtually instantaneous drop in backscattering strengths, especially in the upper 30 m. The very rapid response implied a change in scatterer orientation. The diffuse nature of the scattering layers suggested targets more numerous than fish, while its observability at 50 kHz indicated targets no smaller than a centimetre. Euphausiids were considered prime suspects, an explanation consistent with nighttime euphausiid aggregation in the upper part of the water column, as observed earlier in the Gulf.

Two subsequent developments enabled reliable interchannel comparison of absolute scattering strengths. The first was a four-channel real-time shipboard digital recording system, which was developed by the Metrology Division and was implemented in October 1983. The second was a laboratory methodology for performing accurate absolute system calibration by reflecting acoustic pulses off a water surface in a closed tank, a technique first used in early 1985. The same year saw initial use of BIO's PERCEPTRON image-analysis system to display echograms in a form similar to that of LANDSAT false-colour multispectral scanner images. In this application, echograms at two or more frequencies were overlaid in contrasting primary colours. Biological communities of differing sizes could be easily separated by their resultant colour. This proved invaluable for the initial inspection of databases and for the selection of data for quantitative analysis.

In 1984, an intensive multidisciplinary study of the biology of the inner Scotian Shelf Basins was launched, a study just now reaching completion. The basins - which reach 270 m for the deepest, Emerald Basin - are isolated, enclosed deeps surrounded by a continental shelf typically 80 to 150 m deep. The speculation was that reduced circulation in the deeper portions of the basins might provide a long-term, relatively sheltered environment for developing zooplankton. In June 1984 the first intensive, fully quantitative, multifrequency acoustic study was undertaken in Emerald Basin. A daytime scattering horizon, widespread throughout the basin below 150 m, displayed 50 and 200 kHz comparative backscattering intensities suggestive of large zooplankton, possibly euphausiids. Both BATFISH-mounted optical counters and the BIONESS revealed high densities (1,000 to 2,000/m^3) of large copepods in the same depth range, however. The BIONESS also indicated very low concentrations of euphausiids, typically 0.1/m^3. This presented a dilemma, since scattering theory predicted that neither copepods of 2 to 3 mm in length nor euphausiids at BIONESS-observed abundances were sufficient to produce the observed backscattering levels.

Nevertheless, acoustic scattering from copepods formed our first working hypothesis. To bring theory and experimental results in line, unrealistic physical parameters had to be assumed for the copepods, an approach which had some precedent in the literature (Cochrane and Sameoto, 1987). However, detailed comparison of copepod optical-counter profiles and sonar backscatter profiles, while showing a general correlation, revealed some significant discrepancies. Additional data collected from the basin in 1985 and '86, including backscatter recordings from a 150 kHz bottom-mounted RDI Doppler sonar, revealed a diurnal migratory cycle not observed by deep copepod net sampling. The diurnal cycle appeared to relate the deep daytime layer to a near-surface nighttime layer, as observed in the 1983 light experiment. Euphausiid acoustic-scattering models were further pursued. Modeling euphausiid scattering in the 50 to 200 kHz range proved difficult, since elongate organisms of this size required that their orientation be accounted for. An important series of theoretical papers (Stanton, 1987, 1988) treating scattering from cylindrical targets with orientational dependence assisted us in this problem. We proceeded to develop forward and inverse zooplankton-modeling algorithms based on both the traditional fluid sphere and the newer Stanton cylinder models. The cylinder models permitted specification of orientation, either fixed or with a given degree of randomness consistent with the earlier camera studies in the Gulf of St. Lawrence. Using observed backscattering strengths at 50 and 200 kHz, we utilized a computer to search for optimum estimates of organism length and concentration, assuming a single-sized population of animals. Considerable uncertainty accompanied these estimates because euphausiids are only crudely cylindrical, because single-sized single-component populations are never actually observed in the ocean, and because the finite beam-width of our transducers introduced an additional component of randomness to target orientations which themselves are imperfectly known.

In June 1988, a superior-quality 50 and 200 kHz data set was obtained from Emerald and LaHave Basins. An additional 12 kHz channel was recorded to distinguish fish from zooplankton (Cochrane *et al.*, in preparation). The fish trawler C.S.S. *Alfred Needler*, working with C.S.S. *Dawson*, ran simultaneous mid-water trawls with a l-cm mesh to sample fish and larger euphausiids in depths selected from 12 kHz acoustics data gathered on the *Dawson*. Figure 2 shows a typical example of daytime volume backscattering plotted against depth, with data collected from the central Emerald Basin. A fish layer between 250 m and the bottom echo at 270 m is characterized by roughly similar scattering levels at 50 and 200 kHz and a comparatively strong signature at 12 kHz. Trawling showed this layer to consist largely of silver hake, a noncommercial species in Canada which represents a large biomass in the ecosystem of the Scotian Shelf. Above it appears a horizon which scatters strongly at 200 kHz, less strongly

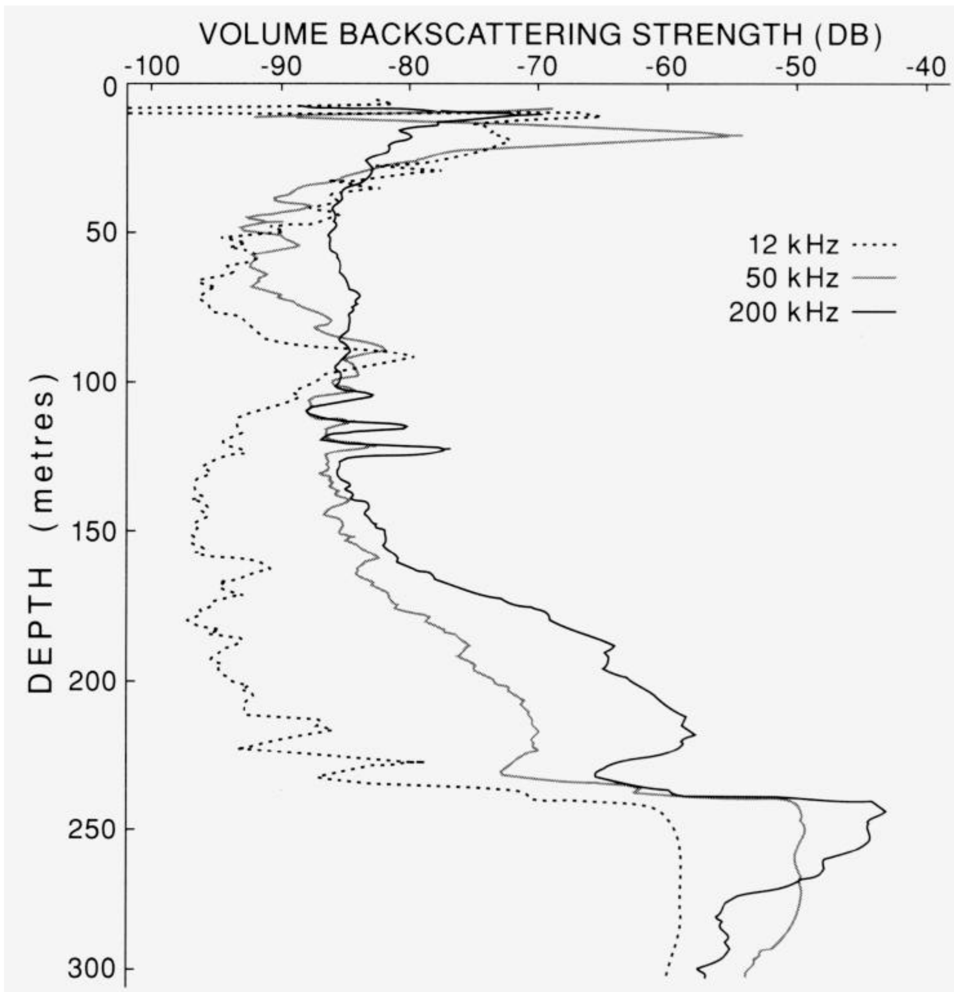


Figure 2. Profiles of volume hackscattering strength plotted against depth at 12, 50, and 200 kHz, using data recorded in central Emerald Basin. The profiles were derived from averaging 300 acoustic transmissions, or 5 minutes of data, starting at 1455 ADT on June 11, 1988. The bottom corresponds to the rapid increase in scattering levels at a depth of about 270 m.

at 50 kHz, and is undetectable at 12 kHz. This horizon, which is most concentrated between 230 and 240 m of depth but is detectable in water as shallow as 150 m, corresponds to the widespread layer observed in the 1984 transect of the basin.

When applied to this layer, our inverse cylinder model yielded a density of 170/m^3 of scatterers 1.6 cm in length. The length lies within a typical range of euphausiid sizes but is smaller than the median 2.8 cm length observed in BIONESS samples. If one forces the organism size to agree with BIONESS samples, concentrations of 20 to 50/m^3 are obtained. An indirect empirical extrapolation based on observations of Antarctic krill suggests about 10/m^3.

In 1988, euphausiid densities sampled with BIONESS still lay in the range of 0.1/m^3, confirming the 1984 deduction that BIONESS was seriously undersampling the population by a factor as large as 100. The avoidance of nets by euphausiids has long been suspected, but not to this degree. To further investigate avoidance, a controlled light source was mounted on BIONESS for the October 1989 sampling season. The hypothesis was that, because euphausiids swim slowly toward bright lights, this would require them to reorient along their direction of motion. This would "freeze" the animals in place by overriding their natural avoidance reaction. The reorientation hypothesis is consistent with the 1983 light experiment, and the "freezing" behaviour is consistent with euphausiid observations made with a Hysub 5000 ROV in Emerald Basin in June 1989. A comparatively enhanced BIONESS catch made while using the sampler light source would verify net avoidance. The 3-knot tow speed of BIONESS and its oblique tow path would prevent significant numbers of euphausiids from concentrating in the net simply because of light attraction. The BIONESS light experiment was performed in October 1989, and the size of the catch taken with the lights on was greater by a factor of almost 10. These new observations achieved through hydroacoustics are forcing scientists to rethink the role of euphausiids in the food chain of the Scotian Shelf Basins.

Improved acoustic instrumentation is on the way. In 1990, DFO will acquire a sonar module which operates on 8 discrete frequencies between 50 kHz and 1 MHz. This sonar, developed by Seastar Instruments Ltd. with extensive assistance from DFO's Metrology Division, can be deep-towed to 300 m. It should allow detection of copepod layers and close-range counting of discrete euphausiid echoes. This sonar and its future extensions should lay the groundwork for an operational acoustic survey system with which variable zooplankton biomasses can be routinely mapped, thereby affording better understanding of the fluctuations in the fish stocks which depend on this biomass as a food source.

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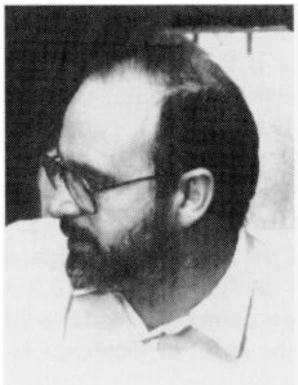
Multi-beam sounding systems: A new ocean-mapping tool for the Canadian Hydrographic Service

B. Burke and P. Hally



B. Burke

P. Hally

The primary mandate of the Canadian Hydrographic Service (CHS) is to chart Canada's navigable waters and to provide related marine data, such as tide tables and sailing directions. Canada possesses one of the world's largest and potentially richest continental shelves. Bathymetric surveys providing detailed coverage are important if Canada is to make appropriate utilization of this valuable resource for national needs.

Canada is a signatory to the 1983 United Nations Convention on the Law of the Sea (UNCLOS). In accordance with the articles contained in this document, Canada could have potential jurisdiction over a coastal regime in excess of 6.8 million km^2. This represents approximately 60% of Canada's total land area (Fig. 1). If the nearshore coastal islands and the Arctic Inner Islands, Hudson Bay, and the Gulf of St. Lawrence are excluded, the remaining oceanic area totals in excess of 4.5 million km^2. It is estimated that bottom surveys of the 4.5 million km^2 would cost in excess of $240 million (Canadian) and require over 42 ship years (250 days per year) to complete (MacNab, 1989).

The Department of Fisheries and Oceans, of which CHS is a component, announced a new Oceans Policy during 1987. One of the key elements in the policy is a new thrust in ocean mapping, aimed at providing detailed hydrographic and geoscientific information on Canada's coastal regime.

A number of new initiatives are underway to establish a viable ocean mapping capability within CHS and the Canadian industrial sector. The acquisition and fitting of a Simrad EM100 Multi-Beam Sounding System on the *Louis M. Lauzier* is an initial step toward fulfilling this goal. In addition, a second EM100 System has been fitted on the SWATH (small waterplane area twin hull) vessel *Frederick G. Creed* and trials are being carried out. A major program to fit the robotic survey vehicle DOLPHIN (deep ocean logging platform with hydrographic instrumentation and navigation) with a multi-beam sounding system is currently underway. The University of New Brunswick (UNB) has commenced a new program of research in ocean mapping. A strategic research grant has been awarded to the university by the National Research Council for studies to be conducted in the area of integrated interpretation tools for large bathymetric data sets. CHS is cooperating with the university in this program and has contracted UNB to carry out studies on the subject of handling such data sets.

Multi-beam sounding systems - basic principles

When it comes to carrying out systematic bathymetric surveys of the ocean, sea surveyors (hydrographers) are at a

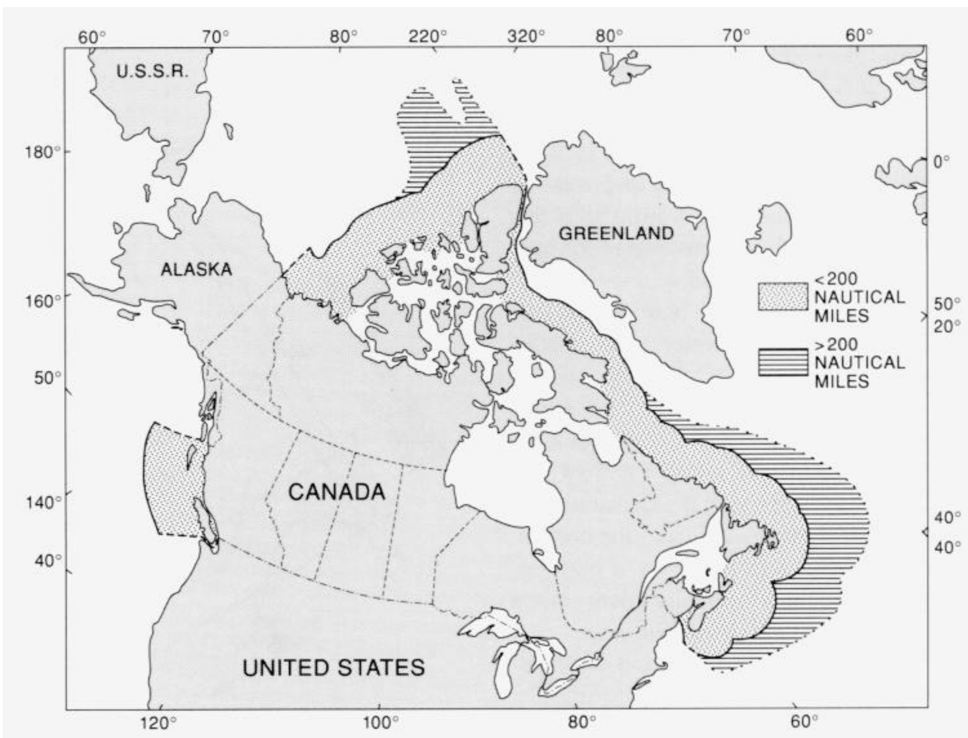


Figure 1. Juridical continental shelf of Canada.

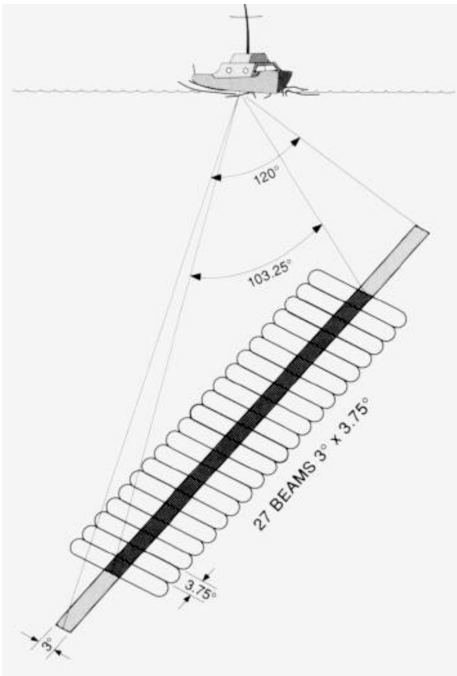


Figure 2. Fan-beam configuration for a multi-beam echosounding system.

great disadvantage compared to their land-based colleagues. Land surveyors are normally able to see what they are measuring and have the advantage that their survey instruments can be located at fixed control points, with the added luxury (in relative terms) of having sufficient time to make as many repeated measurements as may be required to ensure the quality and accuracy of the survey. In comparison, hydrographers normally make their measurements from a moving vessel that is at the mercy of the prevailing sea and weather conditions and may be as little as a few metres to as much as thousands of kilometres from the nearest land.

In order to carry out a bathymetric survey, both position and water depth must be measured. The most common tool for measuring depths is called an echosounder. In essence, it is a device that determines water depth along a narrow line by accurately measuring the transit time of an acoustic signal to and from the bottom. The measurements made by a conventional echosounder normally cover only a small portion of the ocean bottom.

To overcome this limitation and provide increased coverage and accuracy, a new bathymetric survey tool known as the multi-beam echosounding system has been developed (Fig. 2). While it employs the same basic principle of measuring the transit time of an acoustic signal to determine water depth, the equipment and techniques are far more sophisticated than those found in a conventional single-beam echosounder.

In the Simrad EM100, two techniques are employed to achieve accuracy, coverage, and discrimination of bottom detail. The first is referred to as the cross-fan beam technique. It is possible to do beam forming and beam steering using a transducer that comprises a number of individual elements with the appropriate electronics and controls. These systems normally transmit a very wide beam in the athwartship axis of the survey vessel and a very narrow beam in the fore and aft axes (120° by 3° in the case of the EM 100 in the ultrawide sounding mode).

On the receive cycle, the system is able to form a number of very narrow beams (at predetermined angles to a vertical reference) by applying appropriate phase delays and summing the signals from the individual elements of the transducer array. The end result is the capability to measure a wide swath of the ocean floor while obtaining far more geomorphological detail than is possible with conventional echosounders.

One of the limitations of the cross-fan beam technique is that it becomes more and more difficult to determine the slant range accurately on the outer portions of the fan beam. It is more difficult to make the slant-range measurement at high angles of incidence to the bottom surface due to distortion of the acoustic signal (pulse stretching) and the fact that less and less acoustic energy is normally returned to the transducer as the angle of incidence increases.

A second technique that improves the accuracy of the slant-range measurement at higher angles of incidence is known as phase interferometry. If an acoustic signal is transmitted from transducer T1, and both T1 and T2 are used to receive the signal,

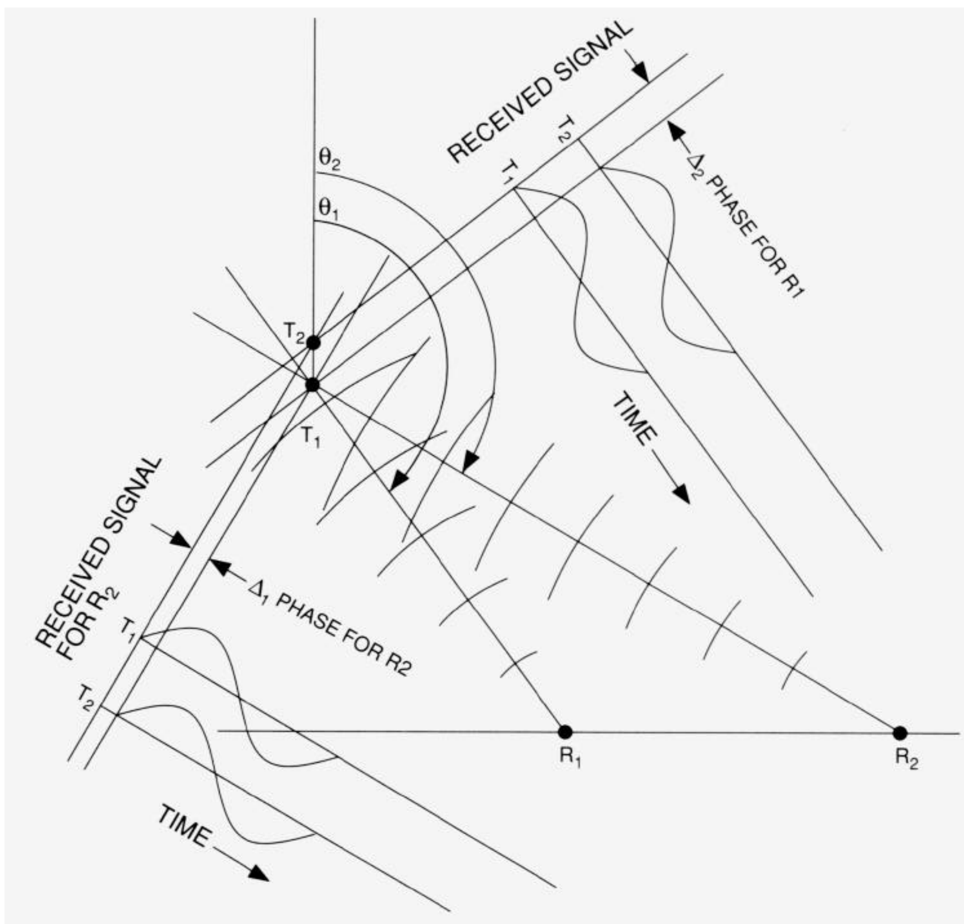


Figure 3. Interferometry concepts.

then it is possible to measure the distance to the reflecting target based on the transit time of the acoustic signal and the angle ø based on the phase difference of the reflected signal received at T1 and at T2. Figure 3 illustrates the arrival phase difference of an acoustic signal from two reflectors, R1 and R2. While the concept is simple, in practice it is difficult to implement. For example, the selection of a frequency that is optimally suited to meet the range, accuracy, and resolution requirements normally entails a compromise. It is also essential to know the transducer's location, its orientation, and the variations in the acoustic characteristics of the media (which are normally difficult to measure in an operational setting) in order to make accurate acoustic measurements. A more comprehensive explanation of the principles of beam forming and interferometry is available in the literature (de Moustier, 1988; Cloet et al., 1987).

The Simrad EM100 system employs both techniques in its range estimations. High-speed bitslice microprocessors compare phase and envelope amplitude values for each beam to obtain an optimum slant-range measurement. Using this technique it is possible to extend the coverage from 1.6 to 2.4 times the water depth, without a significant loss in accuracy. Further development based on the interferometric technique is now being carried out by Simrad to extend the coverage of the EM100 to 8 times the water depth in areas where the depth does not exceed 50 m.

Overview of the Simrad EM100

The Simrad EM100 Multi-Beam Sounding System is a 95 kHz system with a depth capability of 500 m. Its operator can configure it on line to give a multi-beam coverage of 0.7 (narrow), 1.6 (wide), or 2.4 (ultrawide) times the water depth. The size and number of beams are configuration dependent. In the narrow mode the system uses 32 3° by 2° beams, and it uses 27 3° by 3.75° beams in the widest mode. The transducer is mechanically stabilized in pitch and electronically corrected for roll. The amount of data collected is depth dependent and varies from 1 to 4 megabytes per hour. In shallower water the system can cycle faster and, hence, collect more data. All data are logged on a 400-megabyte removable laser disk cartridge which is capable of storing 100 to 400 hours of survey data. Figure 4 shows the on-screen menu used by the operator to run the system.

In order to achieve a high level of accuracy in the depth measurements, it is necessary to correct the slant-range measurements for the motion of the survey vessel. A heave, pitch, and roll sensor is used as part of the EM100 system for motion compensation. Signals from the motion sensor are fed to the Simrad EM100, where the individual slant-range measurements are corrected as they are made. If the propagation velocity of sound in the water column is not constant, the acoustic wave front will not travel in a straight line, a phenomenon known as ray bending. A velocity meter is used to measure the propagation velocity of the water column. This information is fed to the EM100 system, where the beams are also corrected for ray bending.

The data processing package acquired with the Simrad EM100 is composed of two modules. One transfers data from the laser disk to the MicroVAX II processing computer, reformats the raw data files, and preprocesses the navigation and depth data. The second provides the software for creating digital terrain models, contouring, and plotting data. Data are transferred off line from the laser disk to a MicroVAX II - resident file. Separate files (for depth, position, signal strength, and sounder parameters) are created. Position data may be edited and filtered prior to the creation of a tide-corrected XYZ file of all raw depths. The XYZ data are extrapolated to a user-defined grid that is overlaid on the survey area. A number of user-selectable options control the extrapolation and selection criteria.

Once the grid values have been computed, all raw XYZ depth values can be compared with the grid surface and "spikes" can be eliminated. The resulting edited XYZ data set can be used to generate a new set of grid values for the creation of a digital terrain model (DTM). The DTM is then used to generate a number of products. These include contour maps with user-selectable contour intervals and scale, perspective views, cross-sectional profiles between any two locations in the survey area, and a difference map (the two data sets must be in the same grid format). Fig-

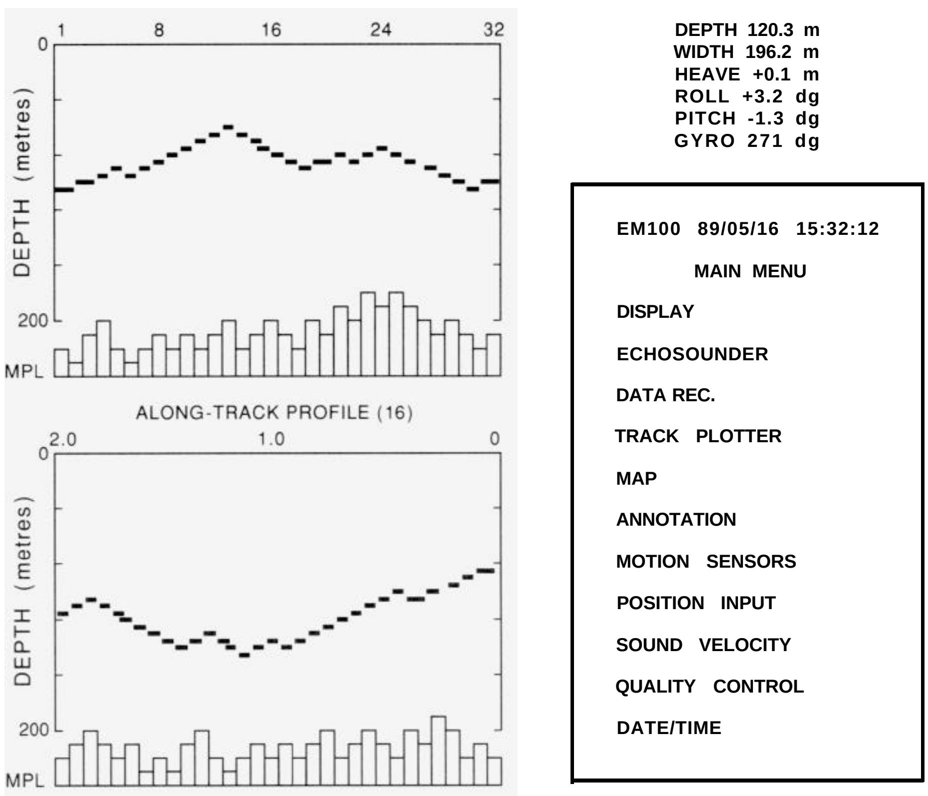


Figure 4. Operator's console display.

ure 5 shows a simplified flow diagram of the data processing. A more detailed description of the data processing package may be found in the literature (Midthassel *et al.*, 1988; Pøhner, 1988).

Operational experience

The *Louis M. Lauzier* was fitted with a Simrad EM100 system during the early part of 1989. In order to accommodate the retractable transducer housing, major structural modifications had to be made to the vessel, including the fabrication and installation of a transducer well and fairing. The vessel was assigned to projects in the Gulf of St. Lawrence and on the coast of Newfoundland during the 1989 survey season. Two months were spent on a survey of the Lower North Shore area of the St. Lawrence River near Havre St.-Pierre and a further two months in the Clode Sound area of Bonavista Bay, Newfoundland. A conventional Elac LAZ 4700 echosounder was operated in parallel with the multi-beam system in order to give an independent check on the performance of the system.

The system functioned well during the first season of operation. Some problems were experienced with the Hippy Data Well sensor, and the transducer ram shaft was damaged when it was struck by an unidentified obstacle. At the start and completion of each survey, calibration checks were carried out. These checks, known as patch tests, involve running a series of lines in opposite directions and at right angles to each other. By carefully analyzing the results it is possible to eliminate fixed biases in pitch, roll, and azimuth. It was quickly realized that the productivity of a survey can be significantly optimized by running lines parallel to the general direction of the contours and by adjusting the survey mode (narrow, wide, and ultrawide). Lines were run in a narrow or wide mode in deeper water and in ultrawide mode in shallower depths in order to keep the coverage as constant as possible.

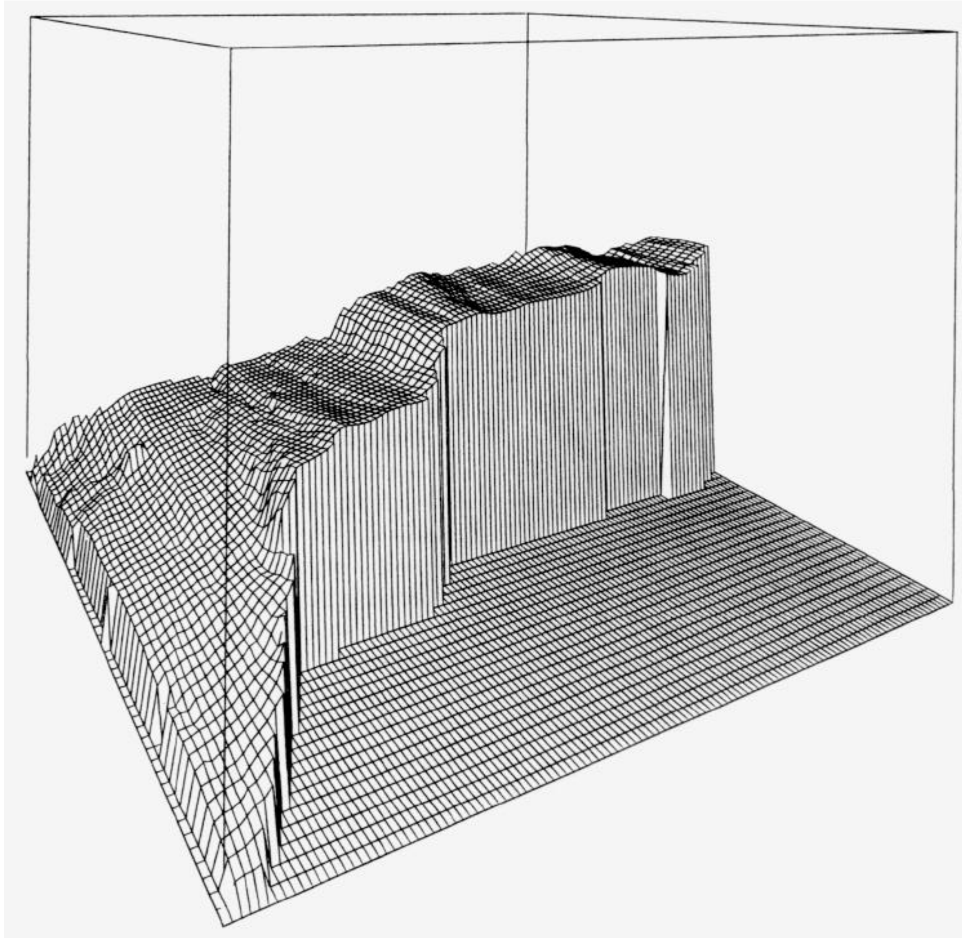


Figure 6. Three-dimensional view of data gathered in a single pass of the EM100.

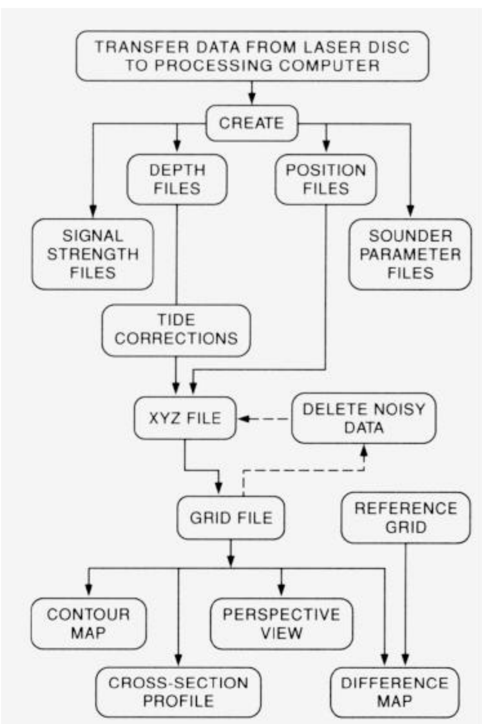


Figure 5. Simplified data processing flow.

Results from some of the data that were gathered are shown in figures 6 and 7. Figure 6 was generated from data gathered by a system installed on the *Frederick G. Creed.* It shows a single swath made in a 500 by 1,250 m area, where the water depths vary from 42 to 324 m. Figure 7 shows the result of a survey that was carried out over the wreck of the *Empress **of** Ireland.* In both cases the data contain more detail than is shown in the figures. In order to make the diagram more legible, the three-dimensional representation has a larger grid than was used to process the data.

Processing of the data has proven to be the major bottleneck in the system. The time required to process data depends upon a number of user-selectable factors, the most significant being the size of the grid cells. If a small grid cell (e.g., 1 to 5 m) is selected, most or all of the geomorphological detail that is contained in the raw data set is retained. However, the processing time may be 5 to 15 times more than was required to gather the data. If a larger grid size is selected (e.g., 10 to 50 m), the processing time will be significantly reduced and an unacceptable level

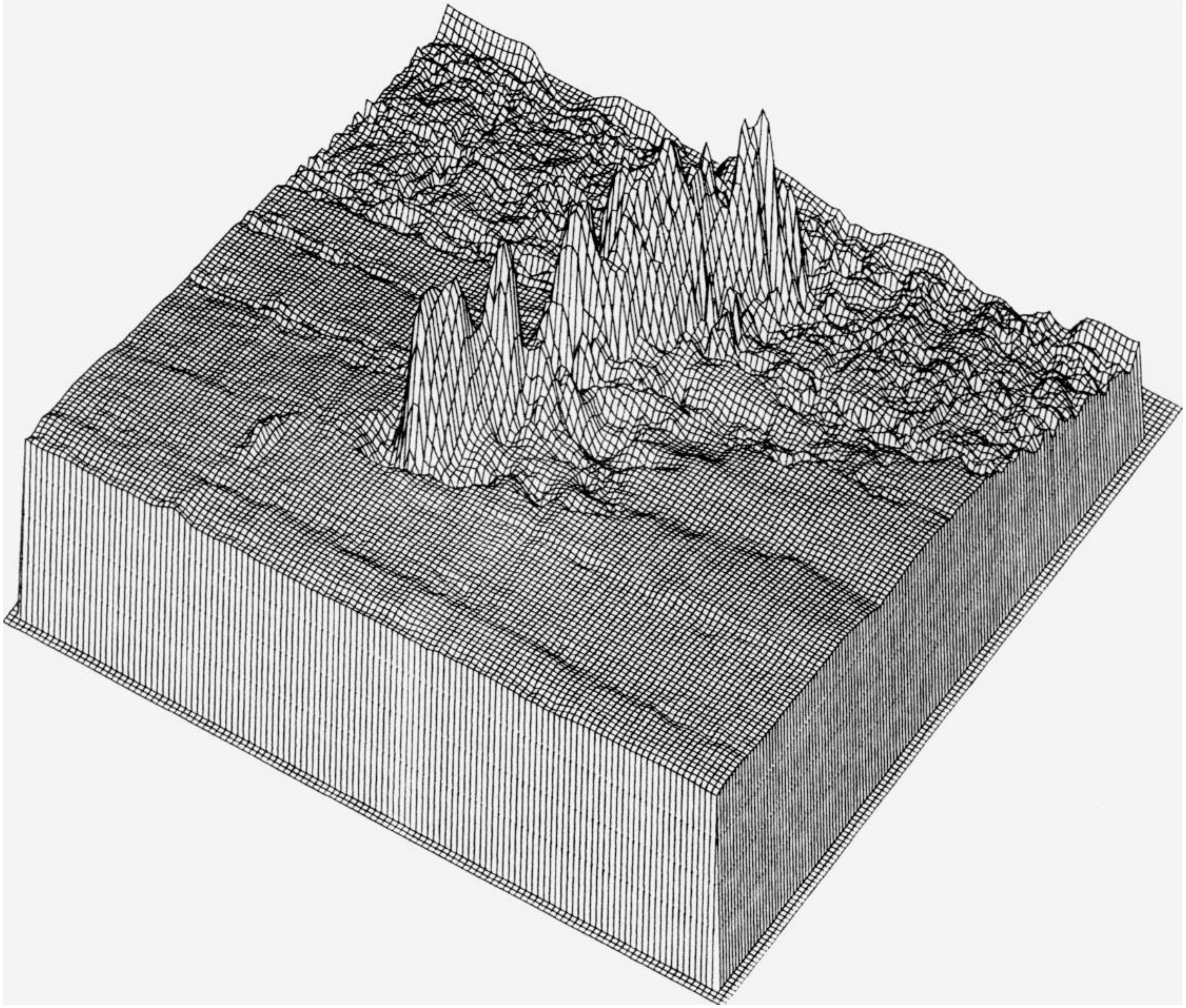


Figure 7. The Empress of Ireland.

of smoothing may mask out shallow depths of critical importance in hydrographic applications. CHS will have to use the existing software in the interim, as no appropriate alternatives are available at this time. It is anticipated that more suitable algorithms will be developed in the near future by the Ocean Mapping Group at UNB.

Conclusions

With the acquisition and implementation of Simrad EM100 Multi-Beam Sounding Systems, CHS has entered a new era of ocean mapping. Work will continue on developing better tools to process, archive, and disseminate the data. In addition, the Department of Fisheries and Oceans will foster development in the private sector with the goal of establishing a viable industry capable of successfully competing in the global market. The next obvious phase is to acquire systems that are capable of measuring the depths encountered in the deepest parts of our coastal regime.

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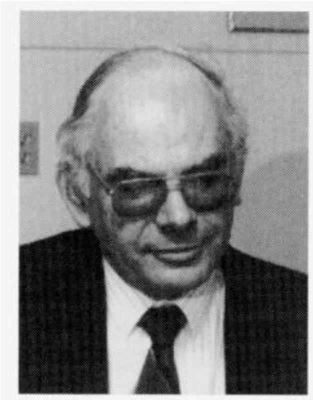
Database management in a marine research institution

D. I. Ross



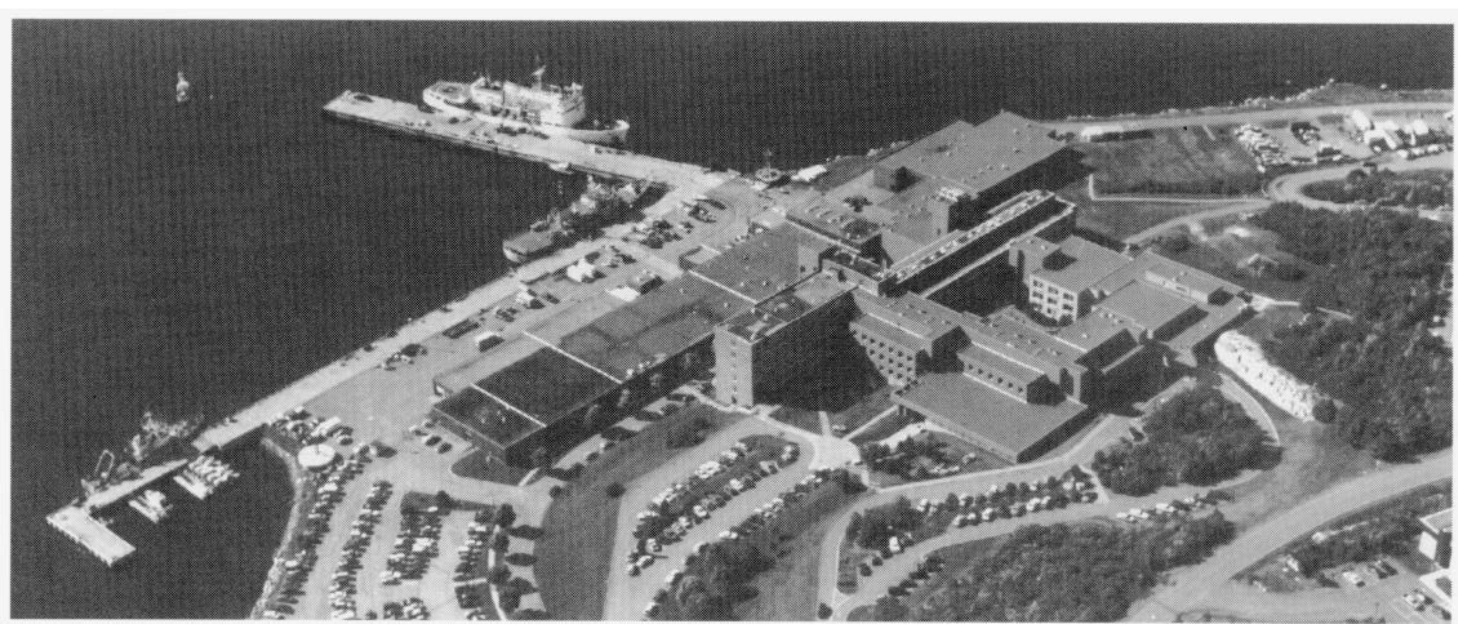
D. I. Ross

A modem marine research institute is built around the collection, processing and analysis, and distribution of scientific information. Much of marine research is also interdisciplinary, requiring the overlay of a variety of data sets for the spatial analysis and evaluation of interacting parameters. The effective manipulation of these data sets to derive appropriate products for resource utilization requires the establishment of a well-developed information infrastructure.

In the past, the required information infrastructure was primarily contained in the scientific literature and printed maps. While still an important source of new ideas and concepts, the quantity of data and the sophistication of our science have grown to such an extent that the computer, and the files of information and data that it contains, has become a standard tool of scientific research. Very few research scientists today are not at least indirect users of a computer terminal, and many are as at home at the computer keyboard now as they were with a pencil and paper ten years ago.

New remote sensing and digital technology has resulted in the rapid increase in pieces of information available to marine scientists for their work, whether they are involved in studying the temperature of the sea surface, ocean currents, the depth of water, or the geology of the seabed and underlying rocks. The enormous increase in computing power available for analyzing data has increased the scientists' ability to analyze the information content in a set of data, and this is resulting in greater demand for precision in the original data and access to increasingly larger databases.

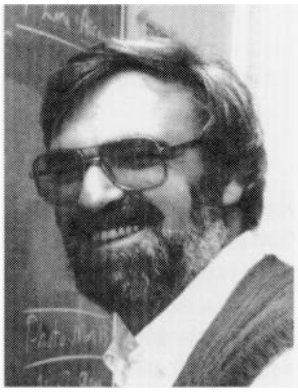
The advent of relational databases has provided a new-capability for designing and integrating information systems. The following three papers discuss the approaches being taken by scientists in three different disciplines of marine science: physical and chemical sciences, hydrography, and geoscience. In each case, the problem is the need to process and analyze an increasingly large volume and diversity of data with a variety of usages and to make this information available to other users. As the volume of data increases, the efficient storage and retrieval can become cumbersome and very inefficient without a suitable means of partitioning the data. The approaches being taken at BIO will ensure efficient access to the data for scientific research and exchange, an essential step toward better understanding of our oceans and their environment.



An aerial view of the Bedford Institute of Oceanography.

Design strategy for an ocean data system

D. Gregory and G. Boudreau



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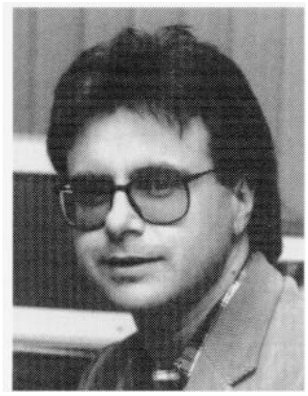


G. Boudreau

The last decade has seen an increased demand for information about issues related to the environment, such as climate change, physical factors influencing fish stock abundance, and offshore petroleum exploration (storm surges, waves, sea ice and icebergs, and oil spill prediction models). This need to understand the complex ocean environment has pushed advances in measurement technology, improving not only conventional ship-based and moored instruments, but also spawning a new generation of satellite-based sensors that are redefining our view of our marine environment. Once primarily a theoretical tool, numerical models have become increasingly sophisticated, to the point where they themselves are considered useful data sources. Underlying this technological capacity to gather information about our oceans is the equally difficult issue of how to manage this information so that it can be effectively used by the science community.

Fortunately, during the same period there have been tremendous advances in computer hardware and software technology, making it possible to translate these volumes of data into meaningful information. Computing power that was previously only available on large mainframe computers is now available on personal computers at a fraction of the cost. Software-based innovations such as relational databases, fourth-generation languages, and geographical information systems (GIS) and their successor, spatial information systems (SISs), are key technologies that permit the power of modem computer hardware to be usefully employed in ocean science. Equally significant, evolving standards permit the simplified interchange of data and software between different computer systems, allowing scientists to work on a variety of computing platforms.

Objectives

Technological developments excite users and managers alike, and the acquisition of the technology is frequently seen as essential and indispensable to keeping abreast of change. A negative consequence of this enthusiasm is technology-driven development, which perceives hardware or software solutions without a plan for integrating the pieces into a system that meets user needs, or, worse, which impacts on scientific objectives in the process of meeting the perceived solution. Objectives must be determined by the information required and the understanding one hopes to attain. Because of the nature of scientific research, an information system requires a framework which can respond to a continual evolution of its requirements without itself becoming obsolete. Over the 10- to 15-year lifetime of a system, one can expect significant advances and innovations in both measurement technology and analysis techniques. Although the exact nature of these changes can only be speculated upon at the system design stage, the system still must cope with these changes when they occur. Also, good sense would dictate that the various system functions (data processing, storage, integrity and security, and scientific analysis and decision support) be accommodated in such a way as to take advantage of commercial software and custom applications developed by other organizations sharing the same objectives.

The relationship of these functions is shown in figure 1. The example could rep-

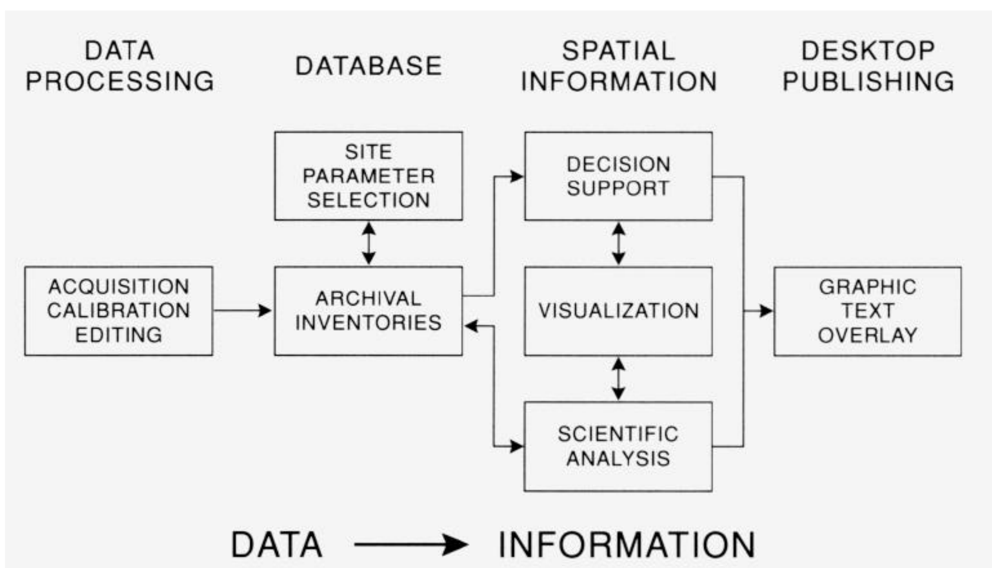


Figure I. Functions of an ocean data system.

resent the information flow from data acquisition through to the generation of an atlas, scientific publication, or *"ad hoc"* query. The sequence in transforming data into "information" involves many subsystems (database, GIS, publishing, etc.) which are not isolated activities but a means to attaining the scientific objectives.

BIO development

At BIO, the Physical and Chemical Sciences Branch is developing an Ocean Information System for marine physical and chemical data. A key objective of the system is to provide a way to easily acquire and assemble data from a range of sources and turn it into meaningful information within reasonable time frames. The system is characterized by two main parts: a processing and analysis component, and a data model. The processing and analysis component employs generic modules that can be assembled in various permutations to "pipe" data between modules, thereby creating the desired processing or analysis algorithm. New functions can be added and obsolete ones removed or revised without affecting the overall system. System software is kept relatively small, as common processing algorithms and data structures are reusable in a variety of contexts. The data model can represent all types of information by creating complex data objects from aggregations of a few elementary data objects known to the model. Data managed by the system can be conventional *in situ* observations, remote-sensed imagery, or computed results from numerical models. Data structures may be predefined or standardized for the data archival requirement while still allowing complete flexibility to define new structures for developmental applications. These two components - the data model and the analysis capability - permit a wide variety of data sources to be interpreted, new parameters derived, and a collection of numerical and graphical data products created. Functions provided by commercial packages, or custom applications developed by other groups, can be integrated by repackaging the software to appear as a system module. Alternatively, a data interchange mechanism can be built from existing components to connect the different systems.

Conclusion

The new Ocean Information System will accommodate and integrate all activities, including data preparation, data storage, scientific analysis, and decision support. Careful systems planning makes this complex process practical and reduces the tedium and expense of bringing together a diverse range of data with varied processing requirements. These data system capabilities will enable us to keep pace with the technological innovations taking place in marine science.

A new approach to spatiotemporal database management

H. A. Boudreau, H. P. Varma, and W. Prime

H. A. Boudreau, W. Prime, and H. P. Varma

During the past few years, in response to requirements to manage, manipulate and disseminate ever-increasing volumes of information, the Canadian Hydrographic Service (CHS) has been committed to the establishment of an Integrated Information Management System. It was recognized that a necessary step toward this goal would be the development and maintenance of a number of databases.

The situation, by no means unique to CHS, was that a multiplicity of types of data (digital, graphic, point representation, area descriptive, nomenclature, etc.) and a variety of usages exist. As for most scientific data, a common thread was reference to time and space. Data were classified as "point" (i.e., where the data elements refer to one discrete geographic location), and "line" (i.e., where the data refer to areas or boundaries). In this way, generalized solutions could be devised which were applicable to many spatiotemporal problems.

A design and implementation strategy was undertaken whereby regional teams were tasked with devising solutions to "subproblems" in the overall context. The largest obstacle to overcome was a lack of defined models or mechanisms to deal with the spatial nature of data in a relational database environment. A CHS working group addressed the issue of point data. The objectives were to design an implementation which would do the following:

- Handle existing data and also be applicable to very large data sets - i.e., sets containing many tens of millions of elements currently and orders of magnitude more in the foreseeable future.
- Conform to the conceptual model in terms of supporting true digital methodology in all phases, from acquisition

to dissemination.

- Be applicable on a global scale, yet still allow some degree of customization.

Initial research and prototyping concentrated on bathymetry (soundings) because it was the data set of greatest volume and density. Solutions to the problems of handling bathymetry would then be applied to other, less dense sets.

Partitioning databases using hydrographic hyperspatial code

Solving the problems of the overwhelming quantities and the unpredictable densities and geographic locations of incoming data necessitated the development of some method to logically and physically subdivide the data into distinguishable sets. The initial (two-dimensional) partitioning model was a binary subdivision; that is, whenever an area was subdivided, each dimension was halved, creating four new areas.

The programmable implementation of this data model led to the hydrographic hyperspatial (HH) code. The HH code was conceived of as a character string uniquely identifying, and at the same time defining, the spatial boundaries of partitions. Any given subpartition was, by definition, one-fourth of a parent and was given an identity code using the characters 0, 1, 2, and 3. The structure was initialized as four quadrants representing the surface of the earth, described in terms of degrees of latitude and longitude (Fig. 1).

Subsequent repartitioning generated new HH codes derived from the existing code. One character is appended to the new code, where the value of that code is a function of the quadrant in which the new cell lies (Fig. 2).

The driving force behind the repartitioning scheme is the data itself. A count is kept of the number of elements within each cell and is allowed to reach only a predetermined maximum. When, and only when, a cell becomes saturated, it is subdivided. A list of existing cells and their corresponding counts is maintained in a database table (Fig. 3).

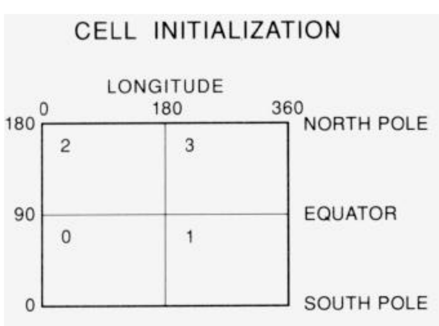


Figure I. Restructuring a geographic coordinate system to a continuous-world coordinate system.

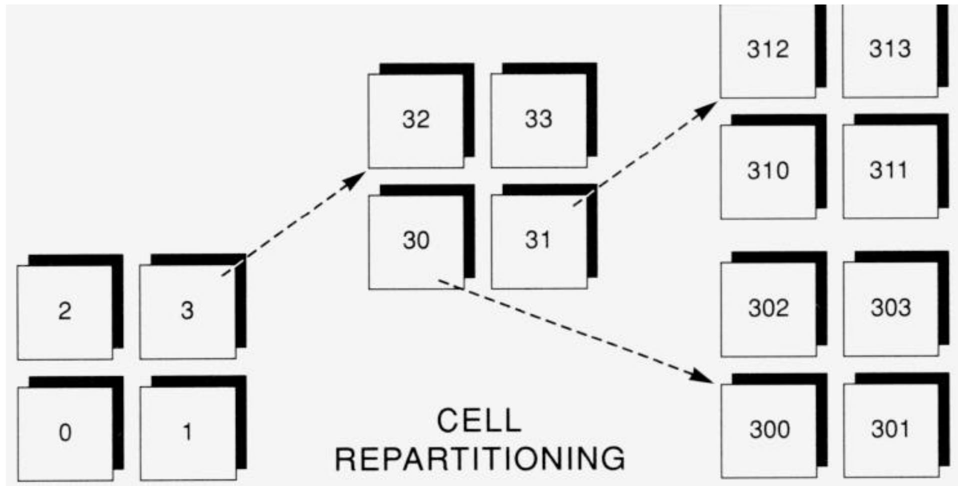


Figure 2. The logical breakdown of object space by storing node points ***on*** *a string.*

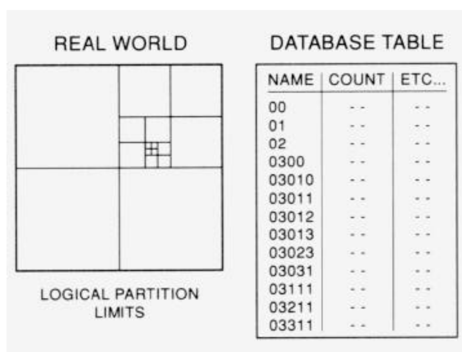


Figure 3. Cells defined as HH-code names in an index table.

The model is extendable to more than two dimensions; hence the term "hyperspatial". Letting the third dimension be time and using the characters 0 through 7, a cube is defined. Each volume element becomes a time element, or "TOXEL" (Fig. 4). By increasing the number of bits needed to define a character, the model is extendable to *n* dimensions.

Within the database, each cell is represented by a unique table. A database table is analogous to a file and contains "records" of attributes for each data element. The table name is itself a substring HH code. Inspection of the resultant structure reveals a number of important properties significant to the implementation:

- The structure is a simple subdivision of coordinates, not an attempt to tessellate the earth's surface; thus it may be generalized in its applications.
- The count of significant characters gives an immediate measure of magnitude on each dimension.
- The process of mapping to real-world coordinates is computationally simple: division by 2.
- The ordered list of HH codes (table names) naturally clusters contiguous data in the spatiotemporal sense. Windowing or grouping becomes trivial.
- Being data-driven, the structure is dynamic. It works equally well for small or large data sets. The table-saturation limit may be defined to suit the avail-

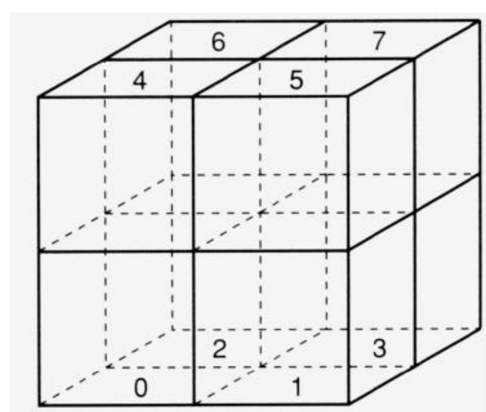


Figure 4. Definition of hypercube.

able computing and storage resources. This points toward achieving truly unconstrained data volumes and densities.

HH functionality

When loading test data, it was found to be convenient to compute an HH code for each data element. Sorting on the code clustered the point, thus minimizing the number of accesses to existing tables, allowing very dense data to plummet to the ultimate repartitioning level, and, in general, increasing the loading efficiency.

Further testing revealed that when an HH code was stored as an attribute for each data point, a new level of functionality became practical and efficient by using the relational power of the database's internal software. That is, the nature of the code is such that by the simple mechanism of comparing or matching strings (or substrings) of characters, natural groupings occur. These groupings can be used for virtually any type of group operation - analytical, statistical, selection, exclusion, display, etc. In short, the groupings define spatiotemporal relations among data points without the cumbersome overhead (pointers, trees, polygons, etc.) of conventional systems.

There is a direct relationship between the number of significant characters and the space to which they refer. This can be expressed in actual measurement or related to some mapping scale. This relationship can be used to advantage to group data elements into "virtual bins", and this grouping is the key to spatiotemporal relations (Fig. 5). The resolution of HH code depends on the number of characters used. In the initial test implementation (two-dimensional using 30 characters), the resolution was 1.63 cm by 1.63 cm on the earth's surface.

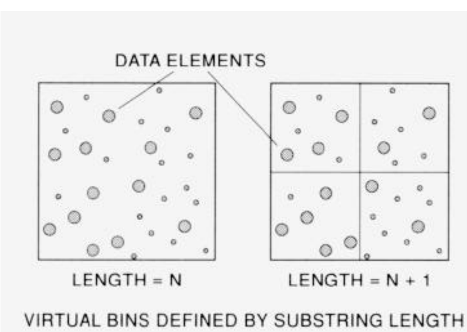


Figure 5. Virtual bins defined by substring length.

Applications may be expressed in standard relational database query language, such as SQL, to perform operations which were not practical before. Examples are provided in table 1:

Table 1. Applications.

STATISTICS
Select <count of items>
From <table>
Where <item = item name>
Group by Substr(HH code, 1, n)

Select <Std Dev(attribute)>
From <table>
Group by Substr(HH code, 1, n)

ANALYSIS
Select <count of items>
From <table>
Where <item = item name>
Group by Substr(HH code, 1, n)

TOPOLOGY
Select <HH code>
From <table>
Where <value within range>
Group by Substr(HH code, 1, n)
(This is a contour)

This functionality demonstrates the capacity to build powerful general-purpose tools which can be applied for data validation, analysis, and representation. A direct correspondence can be made between bins and screen coordinates for display and color fill or shading. Its applications, however, are not restricted to conventional map-making. For example, it is easy to imagine it being used to generate FFTs (Fast Fourier Transforms) using fourth-generation SQL queries.

Prototype

In the fall of 1989, a prototype two-dimension implementation was tested using the ORACLE Relational Database Management System on a dedicated MicroVAX II computer. Approximately 600,000 data points of varying densities and from diverse geographic locations were loaded. It was found that data could be loaded, queries formulated, and data extracted from the database very much as expected.

The performance times were not impressive in themselves. However, at this stage the objective was to demonstrate that the concept would work. Tuning and optimizing the algorithms, as well as determining the most effective computing engine, were defined as later phases of the project.

Interestingly, it is predicted that loading will become more efficient as the database grows in size, because more tables will exist and fewer repartitions will occur. The overall performance on query responses is also predicted to increase dramatically when optimization techniques are employed. These techniques include the binary encoding of the HH string.

Conclusion

The 1989 tests demonstrate that the HH structure can be implemented in a relational database environment. The use of the HH code as a data attribute is consistent with and encourages the digital modeling approach. The ability to express spatial relations through a one-dimension key makes this practical. The partition mosaic is seamless, homogeneous, and scale-independent.

High rates of data compaction are possible because *x* and *y* (e.g., latitude and longitude) and time (year, day, hour, minute, second, and so on) can be encoded. The ability to express topological concepts through the union of HH groupings suggests the design of a line database. The applicability of the structure extends to virtually any type of spatiotemporal data.

Management of marine geoscience data

J. Verhoef and A. Sherin

J. Verhoef and A. Sherin

The characteristic of marine geoscience data which overwhelms one is its diversity: diversity in terms of the disciplines which are covered, diversity in its spatial distribution, diversity in the form and method of collection, and diversity in the relative scientific importance of individual pieces of data. Geoscience is a broad term covering several disciplines in geophysics, geology, geochemistry, and geotechnical engineering. Spatially, geoscience data can be regularly distributed, such as systematic surveys and sidescan mosaics, or it can be sparsely but not necessarily randomly distributed as discrete points. Some data are acquired by automated data-acquisition systems and some are collected by painstaking manual methods requiring conversion to digital form through various data entry techniques. A single reading of magnetics has little scientific significance unless taken together with many other measurements of magnetics, but one carbon 14 date or the confirmed identification of a single fossil can have great scientific significance. In this context, methods of managing geoscience data require great flexibility, and a single approach may not always be appropriate.

At the Atlantic Geoscience Centre (AGC), an integrated approach to data management is being developed, and tools such as relational database management systems and database server hardware have been acquired. At the same time, other approaches more suitable to the type of data being managed are being continued and, whenever possible, linked to the integrated data management approach. The system developed at AGC to manage potential field data in profile is an example of the second kind of system.

Potential field data management

The potential field database consists of data from about 30 institutions and organizations. Figure 1 shows an overview of the procedures and software tools for handling and processing the data. These are based on a suite of approximately 150 programs which run with a standard user interface in a networked VMS environment, and operate on common file formats in order to simplify the exchange of data between software modules.

All profile data are stored in time-ordered multi-field records that can accommodate up to seven concurrently observed parameters. For each cruise, a formatted header record is created containing all available descriptors and qualifiers, such as the type of data and the area limits. For the time being, all data are archived off line on magnetic tapes. At the same time, an online indexing or cataloguing system is implemented for rapid searches and for the semi-automated retrieval of subsets selected according to various criteria (e.g., observations within defined geographic limits). This online index consists of software and two disk files containing summary information which describes the database sufficiently for the purpose of selecting and retrieving data. The first file is organized as an ORACLE database and holds the headers for all data sets (Fig. 2). The second index file holds decimated navigational data for all data sets, along with codes that define the type and availability of the data; this is accessed through custom-built programs. Decimated navigational data consist of a list of critical locations, which is used to reconstruct a ship's track with a specified accuracy; the decimation algorithm typically achieves a compression ratio of a hundred to one.

Extracting profile information from the database is a three-step process (Fig. 2). Step 1: Using the appropriate search pa-

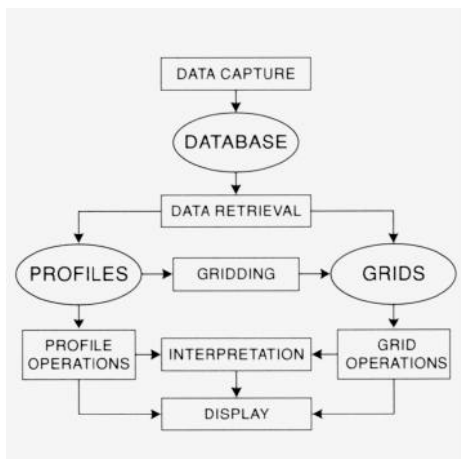


Figure 1. An overview of software tools used to handle, process, and display potential field data.

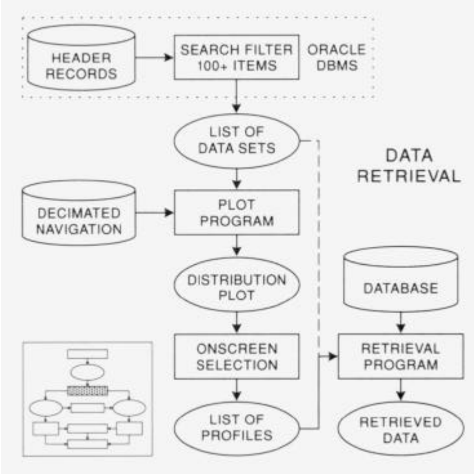


Figure 2. Index and retrieval procedures.

rameters, scan the header records that are stored in the ORACLE database and identify those that meet the requirements. The system creates two procedure files: the first for retrieving the corresponding positions in the decimated navigation file; the second for recovering the selected data from offline storage. Step 2: Invoke the first procedure file on a graphics terminal to create a line plot that indicates the data distribution. This step is optional and its main utility is to select only certain profiles out of the retrieval set. Step 3: Invoke the second procedure file, which specifies which tape(s) to mount in order to retrieve the desired data. The product is a disk file that contains the data.

The foregoing procedures are specifically for time series of observations along ship tracks. Comparable functions are now being developed for data archived in grid form. The basic design of the index and retrieval scheme is flexible enough that it can be expanded and adapted to handle other forms of geographically referenced data, such as depth to seismically reflective layers, multi-beam bathymetry, and digital sidescan data.

Geographical information systems

Another example of the second kind of system is commercial geographical information systems (GISs). Existing relational databases are not well structured for the management of graphical map-based information. For example, SQL (Structured Query Language) does not contain any spatial operands such as “adjacent”, “inside”, or “near”, which are required in order to do efficient retrievals requiring knowledge of the geographic space occupied by data. However, GIS systems provide this capability, together with analytical tools for visualizing, manipulating, and modelling geographical data. These systems have relational database systems as an integral component and provide the link between the spatial aspects of data and the attribute (textual or numeric) aspects of data. AGC is using three GIS products: CARIS (Computer-Aided Resources Information System), a product of Universal Systems Ltd., in Fredericton, New Brunswick, is used for the preparation of AGC’s basin atlas series; PC-ARC/INFO, a product of ESRI Ltd., in Redlands, California, is being used to support AGC’s contribution to the study of Halifax Harbour and approaches; and SPANS (Spatial Analysis System), a product of Tydac Technologies, in Ottawa, Ontario, is being used to analyze iceberg scour data for the Labrador Sea. Figure 3 shows an analysis produced by CARIS for the Labrador Sea basin atlas. Each graphical feature on the map, such as contour and well location, can be linked to the relevant textual and numeric data in a relational database.

Corporate data resource management

To achieve the objective of an integrated corporate database, consensus needs to be reached on the tools to be used to accomplish this. AGC is promoting the acceptance of standards such as SQL, a TCP/IP (Telecommunications Protocol/Internet Protocol) communications protocol, and a UNIX operating system. These software tools are implemented in a networked environment with a single computer acting as the database server. The conversion to this new database environment is currently in progress, with 22 existing separate databases as candidates for integration. They contain diverse types of data, from lithological and biostratigraphic rock descriptions in offshore exploration wells to geotechnical data from surficial samples for the investigation of seafloor stability. The predicted size of this integrated system exceeds 650 megabytes.

Conclusions

The implementation of an integrated database positions AGC for easy connection to the outside world. Initiatives to establish regional and national information infrastructures require AGC to link with databases operated by other govemment and nongovemment agencies, both to more effectively share information and to service the information needs of external clients.

We thank Phil Moir for producing figure 3 with the CARIS GIS software.

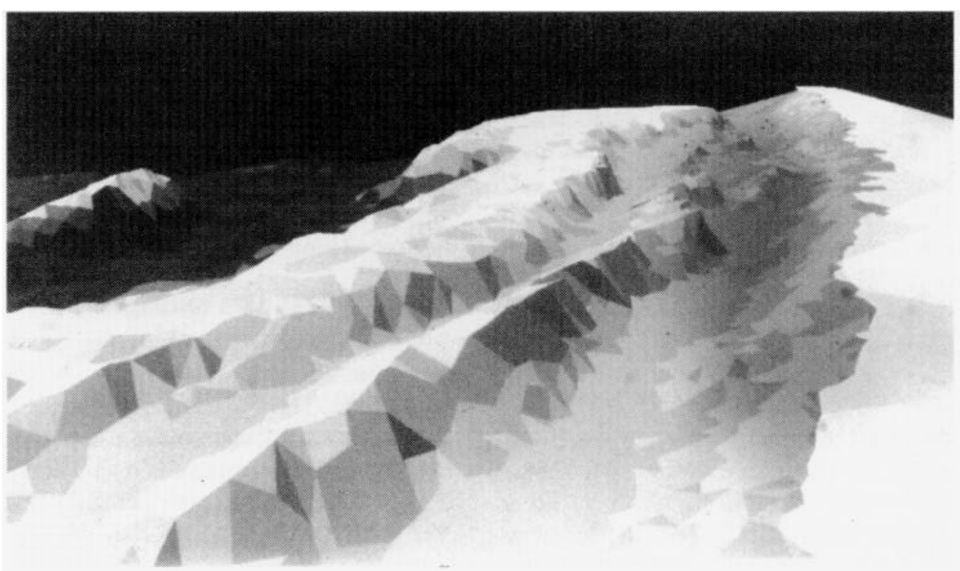


Figure 3. A three-dimensional perspective view of a digital elevation model of Hudson Bay bathymetry, obtained by the Canadian Hydrographic Service near Poste de la Baleine, Quebec. Produced with CARIS GIS software, the view shows ridges caused by dipping rock formations. The viewing direction is south to north, and the vertical exaggeration is 10.

Organization and Staff

The Bedford Institute of Oceanography (BIO), the Halifax Fisheries Research Laboratory (HFRL), and the St. Andrews Biological Station (SABS) are research establishments of the Government of Canada and are operated by the Department of Fisheries and Oceans (DFO), both on its own behalf and, in the case of BIO, for the other federal departments that maintain laboratories and groups at the institute. There are two such departments: the Department of Energy, Mines, and Resources (DEMR); and Environment Canada. The former maintains two units at BIO: the Atlantic Geoscience Centre of the Geological Survey of Canada; and the Canada Oil and Gas Lands Administration Laboratory. Environment Canada also maintains two units at BIO: the Seabird Research Unit of the Canadian Wildlife Service; and the Regional Laboratory of the Atlantic Region's Environmental Protection organization. In leased accommodation at BIO are the following private companies, which do work related to the marine sciences: ASA Consulting Ltd., Brooke Ocean Technology Ltd., Seakem Oceanography, and Seastar Instruments Ltd.

Presented below are the major groups at BIO, and their managers, as at December 1, 1989. In addition to the three research establishments, several staff are located in an office building in Halifax called the Hollis Building (HB). Telephone numbers are included. Note that all numbers at BIO, the Halifax Laboratory, and the Hollis Building should be preceded by 902-426.

DEPARTMENT OF FISHERIES AND OCEANS

Scotia-Fundy Region
Regional Director-General
J.-E. Haché HB/2581

Regional Director Science
S.B. MacPhee BIO/3492

Marine Assessment and Liaison Division
H.B. Nicholls, Head BIO/3246

Scientific Computing Services
D. Porteous, Head BIO/2452

Ocean Technology Promotion
C. Clute BIO/3698

Biological Sciences Branch
M.M. Sinclair, Director HB/3130

R.E. Lavoie, Asst. Director BIO/2147

Marine Fish Division
R.N. O'Boyle, Chief BIO/4890

Benthic Fisheries and Aquaculture Division
(and Director, Halifax Fisheries Research Laboratory)
J.D. Pringle, Chief HFRL/6138

Biological Oceanography Division
T.C. Platt, Chief BIO/3793

Freshwater and Anadromous Division
J.A. Ritter, Chief HB/3573

Aquaculture and Invertebrate Fisheries Division
(and Director, St. Andrews Biological Station)
R.H. Cook, Chief SABS/(506)529-8854

Physical and Chemical Sciences Branch
J.A. Elliott, Director BIO/8478

Marine Chemistry Division
J.M. Bewers, Head BIO/2371

Coastal Oceanography Division
C.S. Mason, Head BIO/3857

Metrology Division
D.L. McKeown, Head BIO/3489

Ocean Circulation Division
R.A. Clarke, Head BIO/2502

Hydrography Branch
Canadian Hydrographic Service (Atlantic)
P. Bellemare, Director BIO/3497

Field Surveys Division
R.C. Lewis, Head BIO/2432

Nautical Publications
S.L. Weston, Head BIO/7286

Hydrographic Development
R.G. Burke, Head BIO/3657

Data Management and Planning
S.T. Grant, A/Head BIO/2411

Tidal Section
C. O'Rielly, A/Head BIO/3846

Management Services Branch
E.J. Maher, Director BIO/7433

Marine Services
W. Cottle, A/Chief BIO/7292

Engineering and Technical Services
D.F. Dinn, Chief BIO/3700

Facilities Management
A. Medynski, Chief BIO/7449

Materiel Management
J. Broussard BIO/3568

Information Systems
C. Crowe, Chief HB/9315

Library Services
A. Oxley, Chief BIO/3675

Administrative Services
D. Brown, A/Chief BIO/7037

Comptroller's Branch
G.C. Bowdridge, Director HB/6166

Accounting and Treasury Operations
S. Lucas, Chief HB/3552

Financial Planning and Analysis
L.Y. Seto, Chief HB/7060

Operational Work Planning Division
R.A. Higgins, Chief HB/2271

Communications Branch
J. Gough, Director HB/3550

Science Communications
M. Roy BIO/6414

DEPARTMENT OF ENERGY, MINES AND RESOURCES

Atlantic Geoscience Centre (Geological Survey of Canada)
D.I. Ross, Director BIO/3448

Basin Analysis
M.E. Best, Head BIO/2730

Environmental Marine Geology
D.B. Prior, Head BIO/7730

Regional Reconnaissance
M.H. Salisbury, Head BIO/5687

Program Support
K.S. Manchester, Head BIO/3411

Administration
C. Racine, Head BIO/2111

ENVIRONMENT CANADA

Marine Wildlife Conservation Division (Canadian Wildlife Service)
E.H.J. Hiscock, Chief BIO/3274

Regional Laboratory (Environmental Protection)
H.S. Samant, Chief BIO/6237

Projects

We present below a list of the projects and individual investigations being undertaken by the Department of Fisheries and Oceans' laboratories in the Scotia-Fundy Region, by the Atlantic Geoscience Centre of the Department of Energy, Mines and Resources, and by Environment Canada's Seabird Research Unit.

For more information on these projects and those of other components at BIO, feel free to write to: Regional Director of Science, Scotia-Fundy Region, Department of Fisheries and Oceans, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2.

BIOLOGICAL SCIENCES BRANCH

A. MARINE FISH AND MARINE MAMMAL STOCK ASSESSMENTS AND ASSOCIATED RESEARCH

1. Herring Assessment and Associated Research (Subareas 4 and 5)
   (R. Stephenson)
2. Haddock Assessment and Associated Research (4TW, 4X, 5Ze)
   (R. O'Boyle)
3. Cod Assessment and Associated Research
   (R. O'Boyle)
4. Pollock Assessment and Associated Research
   (C. Annand)
5. Silver Hake Assessment and Associated Research
   (D. Waldron)
6. Redfish Assessment and Associated Research
   (R. O'Boyle)
7. Flatfish Assessment and Associated Research
   (J. Neilson)
8. Continental Shelf Margin Studies, Including Argentine Assessment
   (R. Halliday)
9. Population Ecology of Sealworm
   (G. McClelland)
10. Population Ecology and Assessment of Seals
    (W. Bowen)
11. Groundfisheries Management Studies
    (R. O'Boyle)
12. Stock Assessment Methods
    (R. O'Boyle)
13. National Sampling Program (Groundfish)
    (K. Zwanenburg)
14. International Observer Program (IOP) Management Research
    (D. Waldron)
15. Groundfish Trawl Surveys
    (J. Hunt)
16. Groundfish Age Determination
    (J. Hunt)
17. Ichthyoplankton Studies
    (P. Hurley)
18. Fisheries Recruitment Variability
    (K. Frank)
19. Otolith Studies
    (S. Campana)
20. Groundfish Tagging Studies
    (W. Stobo)
21. Ecosystem Size Process
    (L. Dickie)
22. Large Pelagics Assessment and Associated Research
    (J. Porter)
23. Groundfish Acoustics Surveys
    (L. Dickie)
24. Pelagic Acoustics Surveys
    (U. Buerkle)
25. Oceanography and Fish Distribution
    (I. Perry)
26. Juvenile Fish Ecology and Surveys
    (J. Neilson)
27. Oceanographic Data Handling
    (J. McRuer, I. Perry)
28. Pelagic Fisheries Management Studies
    (T. Iles)
29. Pelagic Tagging Studies
    (W. Stobo)
30. Reproductive Strategies of Marine Fish
    (T. Lambert)
31. EDP Support
    (R. Branton)
32. Statistical Research
    (S. Smith)
33. Cooperative Science-Industry Groundfish Research and Communication
    (P. Hurley)
34. Stock Structure Studies
    (K. Zwanenburg)

B. INVERTEBRATE AND MARINE PLANT STOCK ASSESSMENTS AND ASSOCIATED RESEARCH

1. Informatics
   (D. Swetnam)
2. Larval Scallop Research
   (M. Tremblay)
3. Population and Fisheries Modelling
   (R. Mohn)
4. Georges Bank and Scotian Shelf Scallop Assessment and Research
   (G. Robert)
5. Offshore Clam Assessment and Research
   (D. Roddick)
6. Scallop Research
   (E. Kenchington)
7. Cape Breton Crustacean Assessment and Research
   (R. Elner).
8. Marine Plants Assessment and Research
   (G. Sharp)
9. Lobster Stock Assessment (LFAs 40 and 41) and Related Research, Including Offshore Scotian Shelf Lobster Stocks
   (D. Pezzack)
10. Lobster Habitat Research and Assessment Methodology
    (R.J. Miller)
11. Lobster Resource Science-Larval Biology
    (G.C. Harding, J. Pringle)

12. Lobster Resource Science and Assessment - LFAs 31 and 32
(J. Pringle)
13. Lobster Assessment and Related Research in Southwest Nova Scotia (LFAs 33 and 34)
(D. Pezzack, J. Tremblay)
14. Wild Mussel Resource Assessment and Research
(G. Sharp)
15. Resource Mapping and Special Projects
(G. Black)
16. Soft-Shell Clam Fishery Research
(S. Robinson)
17. Bay of Fundy Scallop Population Dynamics and Assessment
(S. Robinson)
18. Lobster Stock Assessment (LFAs 35, 36, and 38)
(P. Lawton)
19. Population Dynamics and Ecology of Bay of Fundy Lobsters
(P. Lawton)
20. Invertebrate Biology
(S. Waddy)
21. Resource Potential of Underutilized Invertebrate Species
(S. Robinson, P. Lawton)

C. ANADROMOUS SPECIES STOCK ASSESSMENTS, SALMON ENHANCEMENT, AND ASSOCIATED RESEARCH

1. Salmon Assessment Research
(T. Marshall)
2. Non-Salmonid Assessment Research
(B. Jessop)
3. Salmon Enhancement Research
(R. Cutting)
4. Enhancement and Fish Passage Engineering
(H. Jansen)
5. Fish Culture Engineering
(H. Jansen)
6. Finfish and Invertebrate Introductions and Transfers
(R. Cutting)
8. Hatchery Operations and Production
(G. Robbins)
9. Fish Culture Research
(G. Farmer)
10. Anadromous Species Statistical Data Collection and Analysis
(S. O'Neil)

D. AQUACULTURE RESEARCH

1. Salmon Genetics Research Program
(R.H. Cook)
2. Salmonid Growth, Smolting, and Reproduction
(R.L. Saunders)
3. Invertebrate Biology and Aquaculture
(D. Aiken)
4. Phytotoxin Research
(D. Wildish)
5. Marine Finfish Aquaculture
(K. Waiwood)
6. Aquaculture Ecology Research
(D. Wildish)
8. Environmental Requirements for Early Fish Development
(R. Peterson)
10. Invertebrate Fisheries Research and Aquaculture
(D. Aiken)
11. Invertebrate Nutrition
(J. Castell)
12. Fish Nutrition
(S. Lall)
13. Fish Disease Research
(G. Olivier)
14. Parasitology
(C. Morrison)
15. Molluscan Culture and Phytotoxin Research
(D. Scarratt)
16. Aquaculture Coordination
(D. Scarratt)
17. Fish Health Services Unit
(J. Cornick)

E. BIOLOGICAL OCEANOGRAPHY

1. Bio-Optical Properties of Pelagic Oceans
(T. Platt)
2. Respiration, Nutrient Uptake, and Regeneration of Natural Plankton Populations
(W. Harrison)
3. Physical Oceanography of Selected Features in Connection with Marine Ecological Studies
(E. Horne)
4. Physiology of Marine Microorganisms
(W. Li)
5. Carbon Dioxide and Climate: Biogeochemical Cycles in the Ocean
(T. Platt)
6. Analysis of Pelagic Ecosystem Structure
(A. Longhurst)
7. Carbon and Nitrogen Utilization by Zooplankton and Factors Controlling Secondary Production
(R. Conover)
8. Secondary Production and the Dynamic Distribution of Micronekton on the Scotian Shelf
(D. Sameoto)
9. Biological Stratification in the Ocean and Global Carbon Flux
(A. Longhurst)
10. Nutrition and Biochemistry in Marine Zooplankton
(E. Head)
11. Feeding Dynamics of Zooplankton and Micronekton of the Eastern Arctic
(D. Sameoto)
12. Shore-Based Studies of Under-Ice Epontic and Pelagic Plankton Communities
(R. Conover)
13. Summertime Shipboard Studies in the Eastern Canadian Arctic
(E. Head)
14. Dynamics of Microbial Metabolism and Particle Flux
(P. Kepkay)
15. Mathematical Models of Marine Pelagic Communities
(G. White)
16. Stock Assessment Methods
(G. White)

F. HABITAT RESEARCH

1. Fish Habitat Assessment Advice
(D.C. Gordon)
2. Microbial Ecology
(J.E. Stewart)
3. Microbial-Marine Toxin Interactions
(J.E. Stewart)
4. Physiology of Toxic Algae
(S.R.V. Durvasula)
5. Role of Picoplankton in the Marine Ecosystem
(S.R.V. Durvasula)
6. Phytoplankton Monitoring Program-Nova Scotia
(S.R.V. Durvasula)
7. Kelp and Seagrass Habitat Studies
(K.H. Mann)
8. Inshore Clam Stock Assessment and Related Research
(T.W. Rowell)
9. Inshore Molluscan Habitat Studies
(T.W. Rowell)

10. Scallop Habitat Research
(P. Cranford)
11. Zooplankton Habitat Studies
(G.C. Harding)
12. Benthic Habitat Studies
(D.L. Peer)
13. Benthic/Pelagic Exchanges
(P.D. Keizer)
14. Fish and Habitat Interactions
(S.N. Messieh)
15. Bioenergetics of Marine Mammals
(P.F. Brodie)
16. Size-Dependent and Bioenergetic Processes in Fish Production Habitats
(S.R. Kerr)
17. Aquatic Habitat Production Indices
(P.R. Boudreau)
18. Interactions between Physical and Biological Processes in Marine Habitats
(K.H. Mann)
19. Evaluation of Estuarine and Continental Shelf Habitats
(W.L. Silvert)
20. Contaminant Fluxes in Marine Food Webs
(B.T. Hargrave)
21. Long-Range Transport of Airborne Pollutants (LRTAP) Organic Studies
(B. Hargrave)
22. Long-Range Transport of Airborne Pollutants (LRTAP) Coordination
(D.C. Gordon)
23. Instrumentation Support
(D.P. Reimer)
24. Acid Rain Research (Nova Scotia)
(W. Watt)
25. Freshwater Fish Habitat Assessment and Related Research
(W. Watt)
26. Effects of Low pH on Salmonid Development
(R. Peterson)
27. Impacts of Acid Rain on Salmonid Ecology
(G.L. Lacroix)

PHYSICAL AND CHEMICAL SCIENCES BRANCH

A. OCEAN CLIMATE SERVICES

1. Humidity Exchange over the Sea (HEXOS) Program
(S.D. Smith, R. Anderson)
2. Microstructure Studies in the Ocean
(N.S. Oakey)
3. Near-Surface Velocity Measurements
(N.S. Oakey)
4. Investigations of Air-Sea Fluxes of Heat and Momentum on Large Space and Time Scales using Newly Calibrated Bulk Formulae
(F.W. Dobson, S.D. Smith)
5. The Spin-Down and Mixing of Mediterranean Salt Lenses
(N.S. Oakey)
6. Laboratory Measurements of Velocity Microstructure in a Convective System using Photographic Techniques
(J.M. Hamilton)
7. Labrador Sea Water Formation
(R.A. Clarke, N.S. Oakey)
8. Modelling of the Labrador Sea
(C. Quon)
9. Labrador Current Variability
(R.A. Clarke)
10. Moored Measurements of Gulf Stream Variability: A Statistical and Mapping Experiment
(R.M. Hendry)
11. Newfoundland Basin Experiment
(R.A. Clarke, R.M. Hendry)
12. Problems in Geophysical Fluid Dynamics
(C. Quon)
13. Norwegian/Greenland Sea Experiment
(R.A. Clarke, N.S. Oakey, P. Jones)
14. Baseline Hydrography: North Atlantic at 48°N
(R.M. Hendry)
15. Studies of the North Atlantic Current and the Seaward Flow of Labrador Current Waters
(J.R.N. Lazier)
16. Ship of Opportunity Expendable Bathythermograph Program for the Study of Heat Storage in the North Atlantic Ocean
(F. Dobson)
17. Thermodynamics of Ocean Structure and Circulation
(E.B. Bennett)
18. Shelf Dynamics-Avalon Channel Experiment
(B.D. Petrie, C. Anderson)
19. Batfish Internal Waves
(A.S. Bennett)
20. Data Management and Archival
(D.N. Gregory)
21. Eastern Arctic Physical Oceanography
(C.K. Ross)
22. Water Transport through and in the Northwest Passage
(S.J. Prinsenberg, E.B. Bennett)
23. Seasonal and Interannual Variability in the Gulf of St. Lawrence
(G.L. Bugden)
24. The Gulf of St. Lawrence-Numerical Modelling Studies
(K. Tee)
25. Tidal and Residual Currents-3-D Modelling Studies
(K. Tee)
26. Circulation and Air/Sea Fluxes of Hudson Bay and James Bay
(S. Prinsenberg)
27. Developing an Efficient Method for Modelling Three-Dimensional Shelf and Slope Circulations
(K. Tee)
28. CTDs and Associated Sensors
(A.S. Bennett)
29. Real-Time Data Acquisition
(A.S. Bennett)
30. Mooring Systems Development
(G. Fowler, J. Hamilton, A. Hartling, R.F. Reiniger)
31. Handling and Operational Techniques for Instrument/Cable Systems
(J.-G. Dessureault, R.F. Reiniger)
32. Climate Variability Recorded in Marine Sediments
(J. Smith)
33. The Carbonate System and Nutrients in Arctic Regions
(E.P. Jones)
34. Distribution of Sea Ice Meltwater in the Arctic
(F.C. Tan, P. Strain)
35. Intergyre Exchange: Flow Across 50°W South of the Grand Banks
(R. Hendry)
36. WOCE Studies
(R.A. Clarke)

B. MARINE DEVELOPMENTS AND TRANSPORTATION

1. Oil Trajectory Analysis
(D.J. Lawrence)
2. Winter Processes in the Gulf of St. Lawrence
(G. Bugden)
3. Point Lepreau Environmental Monitoring Program
(J.N. Smith)
4. Marine Emergencies
(E.M. Levy)
5. A Novel Vibracorer for Surface, Subsurface Remote, or ROV Support Operation
(G. Fowler)

C. OFFSHORE ENERGY RESOURCES

1. Studies of the Growth of Wind Waves in the Open Seas
(F.W. Dobson)

2. Iceberg Drift Track Modelling
(S.D. Smith)
3. Labrador Coast Ice
(S. Prinsenberg, I. Peterson)
4. Gulf of St. Lawrence Ice Studies
(G. Bugden)
5. Wind Sea Dynamics
(W. Perrie, B. Toulany)
6. Current Measurements near the Ocean Surface
(P.C. Smith, D.J. Lawrence, J.A. Elliott, D.L. McKeown)
7. Modelling of Ice and Icebergs Flowing along the Labrador and Baffin Island Coasts
(M. Ikeda)
8. A Large-Scale Circulation in the Labrador Sea and Baffin Bay
(M. Ikeda)
9. Labrador Ice Studies-Field Program
(I. Peterson, S. Prinsenberg)
10. Storm Response in the Coastal Ocean: The Oceanographic Component of the Canadian Atlantic Storms Program
(P.C. Smith, W. Perrie, F.W. Dobson, D.A. Greenberg, D.J. Lawrence)
11. Dynamical Origins of Low-Frequency Motions over the Labrador/Newfoundland Shelf
(D. Wright, J. Lazier, B. Petrie)
12. Labrador Ice Margin Studies
(C. Tang, M. Ikeda)
13. Current Surges and Mixing on the Continental Shelf Induced by Large Amplitude Internal Waves
(H. Sandstrom, J.A, Elliott)
14. Oceanography of the Newfoundland Continental Shelf
(B.D. Petrie, D.A. Greenberg)
15. Study of Current Variability and Mixed Layer Dynamics on the Northeastern Grand Banks
(C.L. Tang, B.D. Petrie)
16. Anemometers for Drifting Buoys
(J.-G. Dessureault, D. Harvey)
17. Bottom-Referenced Acoustic Positioning Systems
(D.L. McKeown)
18. Ship-Referenced Acoustic Positioning Systems
(D.L. McKeown)
19. Doppler Current Profiler
(J. Whitman)
20. Development of a Lagrangian Surface Drifter
(D.L. McKeown, G. Fowler)
21. Bottom-Mounted Acoustic Current Profiler
(D. Belliveau, N. Cochrane)
22. Techniques to Recover or Refuel the Submarine DOLPHIN under Way
(J.-G. Dessureault, R. Vine, ETS)
23. Petroleum Hydrocarbon Components
(E. Levy)
24. Enhanced Biodegradation of Petroleum in the Marine Environment
(E. Levy, K. Lee)
25. Trace Elements in the Marine Environment
(P. Yeats)
26. Application of Measurements of Hepatic Microsomal Mixed Function Oxidase (MFO) Activity in Winter Flounder as a Petroleum Pollution Monitoring Tool
(R.F. Addison, J.F. Payne, J. Osborne)
27. Petroleum Hydrocarbon Stress to Juvenile Fish
(J.H. Vandermeulen)
28. Contaminant Cycling in Estuarine Waters
(J.H. Vandermeulen)
29. Measurement of Ocean Waves during CASP
(F.W. Dobson)
30. A Trawl-Proof Bottom Mount for Oceanographic Instruments
(J.-G. Dessureault)
31. System to Allow the Use of Towed Subsurface Instrumentation in Light-to-Moderate Sea Ice
(R.A. Clarke)
32. Horizontal and Vertical Exchange on Georges Bank
(J. Loder, K. Drinkwater, E. Horne, N. Oakey)
33. Oceanic CO2
(E.P. Jones)
34. Tainting of Scallops by Oil-Based Drilling Mud Cuttings
(R.F. Addison)
35. Oil Volatilities
(E. Levy)
36. Wave-Wind Field Interactions
(F. Dobson, S. Smith, W. Perrie)
37. Oceanographic Data Management System
(D. Gregory, G. Boudreau)
38. Wave and Ice Dynamics
(W. Perrie, B. Toulany)
39. Ocean Currents over Atlantic Canada Waters Using Satellite Altimeters and Models
(M. Ikeda)
40. Pollution from the Offshore Oil Industry: Putting It into Perspective
(E. Levy)
41 Development of an Ice-Resistant Mooring Assembly (IRMA)
(G. Fowler, D. Belliveau, J. Hamilton)
42. Development of Continuous Ocean Data Acquisition Systems (CODA)
(D. Belliveau, J. Hamilton, G. Fowler)
43. Development of a Platform for Atmospheric Data in Real Time (PADIRT)
(J. Hamilton, G. Fowler, D. Belliveau)
44. Sea-Ice Flux onto Newfoundland Shelves
(S. Prinsenberg)
45. CASP II Oceanography
(P. Smith)

D. LIVING RESOURCES

1. Circulation off Southwest Nova Scotia: The Cape Sable Experiment
(P.C. Smith, K. Tee, R. Trites)
2. The Shelf Break Experiment: A Study of Low-Frequency Dynamics and Mixing at the Edge of the Scotian Shelf
(P.C. Smith, B.D. Petrie)
3. Circulation and Dispersion on Browns Bank: The Physical Oceanographic Component of the Fisheries Ecology Program
(P.C. Smith)
4. Long-Term Monitoring of the Labrador Current at Hamilton Bank
(J. Lazier)
5. Long-Term Temperature Monitoring
(D. Gregory, B. Petrie, E. Verge)
6. Development of a Remote-Sensing Facility
(C.S. Mason, B. Topliss, L. Payzant)
7. Horizontal and Vertical Exchange on the Southeast Shoal of the Grand Bank
(J.W. Loder, C.K. Ross)
8. Towed Biological Sensors
(A.W. Herman)
9. The Dynamics of Primary and Secondary Production on the Scotian Shelf
(A.W. Herman)
10. Vertical-Profiling Biological Sensors
(A.W. Herman)
11. Zooplankton Grazing and Phytoplankton Production Dynamics
(A.W. Herman)

12. Moored Biological Sensors
(A.W. Herman, M.R. Mitchell)
13. Optical Properties of Canadian Waters
(B.J. Topliss)
14. Biological Arctic Instrumentation
(A. Herman, D. Knox)
15. Automatic Winch Control for Towed Plankton Samplers
(M. Mitchell, J.-G. Dessureault, A. Herman, S. Young, D. Harvey)
16. Multi-Frequency Acoustic Scanning of the Water Column
(N.A. Cochrane)
17. Fish Aging from $^{210}Pb/^{226}Ra$ Measurements in Otoliths
(J.N. Smith)
18. Growth Rates of the Sea Scallop *(Placopecten Magellanicus)* Using the Oxygen Isotope Record
(F.C. Tan, D. Roddick)
19. Water Mass Analysis for the NAFO Area
(R.W. Trites, K. Drinkwater)
20. Effects of Hudson Bay Outflow on the Labrador Shelf
(K. Drinkwater)
21. Larval Transport and Diffusion Studies
(R. Trites, T.W. Rowell, E.G. Dawe)
22. Climatic Variability in the NAFO Area
(R. Trites, K. Drinkwater)
23. Environmental Variability - Correlations, Patterns, and Response Scales
(K. Drinkwater, R. Trites)
24. Baffin Island Fjords
(R.W. Trites)
25. Variability and Origin of the Cold Intermediate Layer on the Labrador and Newfoundland Shelves
(S.A. Akenhead, J.R.N. Lazier, J.W. Loder, B.D. Petrie)
26. Mapping Particle Distributions with a ROV
(D.L. McKeown, D. Sameoto, N.S. Oakey, G. Steeves)
27. Ocean Feature Identification via Multi-Spectral *In-Situ* and Remote-Sensing Techniques
(B. Topliss)
28. TLC (Temperature, Light, Current) Recorder
(J.-G. Dessureault, B. Beanlands)
29. Exchange between Offshore Waters and the Estuaries, Inlets, and Coastal Embayments of the Scotia-Fundy Region
(G. Bugden)
30. Physical Oceanography in Conjunction with the Phytoplankton Profiling Program
(G. Bugden)
31. Classification of Estuaries, Inlets, and Coastal Embayments
(R.W. Trites, B.D. Petrie)
32. Quoddy Region Oceanography
(R.W. Trites)
33. Halifax Harbour Studies
(D.J. Lawrence, B. Petrie)
34. Acoustic Doppler Current Profiler Sidelobe Deflectors
(D. Belliveau)
35. Advanced Technology Multifrequency Sonar
(N.A. Cochrane)
36. Development of Finite Element Models for Coastal and Shelf Circulation
(D. Greenberg)
37. Laser Particle Counter
(A.W. Herman, E.F. Phillips, D. Knox, M. Mitchell, S. Young)
38. Optical Microzooplankton Detector
(A.W. Herman, E.F. Phillips, D. Knox, M. Mitchell, S. Young)
39. Diagnosis of Current Measurement Problems with Aanderaa Paddle-Wheel Current Meters in High Flows
(J.M. Hamilton, G.A. Fowler)

E. BIOGEOCHEMISTRY

1. *In-Situ* Sampling of Suspended Particulate Matter
(G. Fowler, B. Beanlands)
2. Estuarine and Coastal Trace Metal Geochemistry
(P.A. Yeats, D.H. Loring)
3. Sediment Geochronology and Geochemistry in the Saguenay Fjord
(J.N. Smith)
4. Organic Carbon Transport in Major World Rivers: The St. Lawrence, Canada
(R. Pocklington, F. Tan)
5. Isotope Geochemistry of Major World Estuaries
(F.C. Tan, J.M. Edmond)
6. Trace Metal Geochemistry in Estuarine Mixing Zones
(P. Yeats, J. Dalziel)
7. Trace Metal Geochemistry in the North Atlantic
(P.A. Yeats, J. Dalziel)
8. Natural Marine Organic Constituents
(R. Pocklington)
9. Radionuclide Measurements in the Arctic
(J. Smith)
10. Carbon Isotope Studies on Particulate and Dissolved Organic Carbon in Deep Sea and Coastal Environments
(F.C. Tan, P. Strain)
11. Joint Canadian/German Caisson Experiments
(D.H. Loring, F. Prosi)
12. Development of Methods for Studies of the Atmospheric Input of Organochlorines to the Northwest Atlantic and Arctic
(R.F. Addison, G.C. Harding, B.T. Hargrave)
13. Trace Metal Transport into the Western North Atlantic
(P. Yeats)
14. Low Molecular Weight Hydrocarbons: Potential Contributions to the Carbon and Energy Requirements of Offshore Scallops and Prey of Juvenile Galoids on Georges Bank
(E. Levy, F. Tan, K. Lee)
15. The Contribution of Natural Seep-age to Benthic Productivity on the Continental Shelf off Baffin Island
(E.M. Levy, F.C. Tan, K. Lee)
16. Defining Depositional Conditions from the Grain-Size Spectra of Bottom Sediments
(K. Kranck)
17. The Role of Flocculation in the Flux of Particulate Matter in the Marine Environment
(K. Kranck)
18. Chemical Reactivity in the Surface Ocean
(P. Strain)

F. TOXICOLOGY, CONTAMINANTS, AND HABITAT

1. Canadian Marine Analytical Chemistry Standards Program
(J.M. Bewers, J. Uthe, P. Yeats, D. Loring)
2. International Activities
(J.M. Bewers, P.A. Yeats, D.H. Loring, J. Uthe, R. Misra, R. Addison)
3. Heavy-Metal Contamination of Sediments and Suspended Matter on the Greenland Shelf
(D.H. Loring, G. Asmund)

4. Risk Assessment of Toxic Chemicals
(J.F. Uthe, R. Misra, C.L. Chou, N. Prouse)
5. Habitat Assessment and Related Research-Acid Rain
(J. Uthe, P. Yeats, G.B. Sangalang)
6. Risk Assessment of Organic Chemicals to Fisheries
(V. Zitko)
7. Biochemical Indicators of Health of Aquatic Animals
(K. Haya, B.A. Waiwood, L.E. Burridge)
8. MFO Enzyme Induction by PCBs and PCB Replacements
(R.F. Addison)
9. Organochlorines in Seals
(R.F. Addison)
10. Sub-Lethal Contaminants: Long-Term Fate and Effects of Petroleum Hydrocarbon Pollution in Aquatic Systems
(J.H. Vandermeulen)
11. Interaction of Toxicity and Mutagenicity in Contaminated Environmental Samples
(J.H. Vandermeulen)
12. Aquatic Toxicology of Marine Phytotoxins
(K. Haya, L. Burridge, B.A. Waiwood)
13. Development of Multivariate-Multicomponent Contaminant Monitoring Strategy
(R. Misra, J. Uthe, D. Loring, P. Yeats, C. Chou)
14. Investigations into Amino Acid Shellfish Toxins
(R. Pocklington)
15. Molluscan Toxins, Techniques, and Improvements
(V. Zitko)

HYDROGRAPHY BRANCH

A. HYDROGRAPHY

1. Coastal and Harbour Surveys (Atlantic Provinces):
Dipper Harbour, N.B.
Annapolis Royal & Annapolis River
Point Lepreau to Saint John, N.B.
St. John's Bay, Northwest Nfld.
(V.J. Gaudet)
Restigouche, N.B.
(G. Rockwell)
St. John's Harbour, Nfld.
Cape St. Francis, Nfld.
Bonavista Bay, Nfld.
Smith & Random Sound-Trinity Bay, Nfld.
Greenspond Island to Cape Freels, Nfld.
Bacalhao Island to Black Island, Twillingate, Nfld.
Lewisport and Botwood, Nfld.
Springdale, Nfld.
St. Anthony, Nfld.
Punchbowl, Labrador
(J. Goodyear)
2. Coastal and Harbour Surveys (Labrador and Arctic):
Tuchialic Bay, Labrador
Big Bay, Labrador
Cape Kiglapait, Labrador
Loks Land, Baffin Island
Cape Mercy, Baffin Island
Kangok Fiord, Baffin Island
Cape Jamieson to Cape Christian, Baffin Island
(Contract)
Nain, Labrador
(G. Henderson)
Griese Fiord
Resolute Passage & Allen Bay
South Bathurst Island
(E.J. Comeau)
3. Offshore Multi-Disciplinary Surveys:
Scotian Shelf, N.S.
(G. Henderson)
4. Sweep Surveys-Ports and Harbours of the Atlantic Coast:
Barrington Bay, N.S.
Shelbume, N.S.
Lockeport, N.S.
Liverpool, N.S.
Riverport, N.S.
Halifax Harbour & Bedford Basin
Porters Lake, N.S.
Sheet Harbour, N.S.
Canso Harbour, N.S.
Sydney, N.S.
Pictou, N.S.
Lameque, N.B.
Caraquet, N.B.
(D.A. Blaney)
5. Revisory Surveys:
Chance Harbour, N.B.
Brier Island, N.S.
(V.J. Gaudet)

B. TIDES, CURRENTS, AND WATER LEVELS

1. Ongoing Support to CHS Field Surveys and Chart Production
(C. O'Reilly, O. Nadeau, C.P. McGinn, G.B. Lutwick, F. Carmichael)
2. Operation of the Permanent Tide and Water-Level Gauging Network
(C. O'Reilly, O. Nadeau, C.P. McGinn, G.B. Lutwick, F. Carmichael)
3. Review and Update of Tide Tables and Sailing Directions
(C. O'Reilly, O. Nadeau)
4. Scientific and Engineering Project Support: Calibration and Maintenance of Portable and Submersible Gauges; Tidal Analysis of Minas Basin (Five Islands) for Queens University; Tidal Survey-Head of Tide Miramichi River; Development of Remote Arctic Tide Gauge (with ARGOS satellite link and underwater electro-magnetic data communications); Development of Coastal Ocean Water Level Information System (COWLIS); Development of Tides/Currents Geographic Information System (Database/Modelling)
(C. O'Reilly, O. Nadeau, C.P. McGinn, G.B. Lutwick, F. Carmichael)

C. NAUTICAL PUBLICATION PRODUCTION

1. Chart Production:
10 New Charts (in house)
7 New Charts (by contract)
13 New Editions
2 New Editions for LORAN-C
30 Chart Correction Patches
200 Notices to Mariners
(S. Weston, F. Miller, A. Hantzis, E. Lischenski)
2. Sailing Directions: Publication of Sailing Directions, Nova Scotia, Atlantic Coast and Bay of Fundy
(S. Weston, R. Pietrzak)

D. DATA MANAGEMENT AND PLANNING

1. Hydrographic Data Centre
Updates and Maintenance of the Source Directory Files Management System
(K. MacDonald, S. Nickerson)
Interaction with the Validation Unit
(K. MacDonald, S. Nickerson)
Development of a National Files Management System
(K. MacDonald)
2. Validation:
Validation of New Charts
4847 Conception Bay, Nfld.
(J. LaRose, B. McCorriston)

4124 Seal Cove, L'Etang, N.B.
(S. Dunbrack)
Validation of New Editions
7552 Bellot Strait and Approaches
(R. Haase)
4394 LaHave River to West Ironbound
(F. Burgess)
4395 LaHave River, N.S.
(R. Haase)
7511 Resolute Passage
(G. Stead)
Validation of Incoming Documents from Outside Agencies
249 documents
3,000 Notices to Shipping and Foreign Notices to Mariners
47 Digitization of Field Sheets
(W. Burke, A. Hantzis, G. Stead, S. Dunbrack, C. O'Reilly, G. Rankine, D. Roop, R. Haase)

3. Navigation
   BIONAV Maintenance and User support
   (H. Boudreau)
   LORAN-C Chart Latticing
   (N. Stuifbergen)
   Navigation-User Support and Training
   (H. Boudreau, N. Stuifbergen)
4. Database Management Systems
   Point Data Sets: Phase 1 - Proof of Concept
   (H. Boudreau, H. Varma)
   Point Data Sets: Phase II - Bathymetry Prototype
   (H. Boudreau, H. Varma)

E. HYDROGRAPHIC DEVELOPMENT

1. Research Coordination and Development
   (R.G. Burke)
2. DOLPHIN Trials
   (R.G. Burke, G. Costello)
3. *F.C.G. Smith* Data Processing Software
   (S. Forbes)
4. Enhancing Automatic Field Surveys
   (K. White, S. Forbes)
5. Enhancing Computer-Assisted Chart Production Techniques
   (S. Forbes, K. White)

ENVIRONMENT CANADA, CONSERVATION AND PROTECTION, CANADIAN WILDLIFE SERVICE, SEABIRD RESEARCH UNIT

A. DISTRIBUTION AND ECOLOGY OF SEABIRDS IN ATLANTIC CANADA AND THE EASTERN CANADIAN ARCTIC

1. Distribution and Population Trends of Coastal Seabirds in Atlantic Canada (Gulls, Terns, and Cormorants)
   (A.R. Lock)
2. Studies of Tern Reproduction and Survival, and Management for Population Enhancement.
   (A.R. Lock)
3. An Integrated Study of a Mangrove Lagoon in Oaxaca State, Mexico
   (A.R. Lock, M. Malone)
4. Habitat Use and Winter Populations of Birds Using Wetlands on the Pacific Coast of Mexico
   (A.R. Lock)
5. Seabird Colony Registry-Computerized Database Management System for Colonially Breeding Seabirds in Eastern Canada
   (D.N. Nettleship, G.N. Glenn)
6. Development of Management Methods for Populations of Threatened Seabirds
   (D.N. Nettleship)
7. Patterns of Distribution and Abundance of Breeding Seabirds in Northeastern North America
   (D.N. Nettleship)
8. Thick-Billed Murres *Uria lomvia* in the Canadian High Arctic: Status, Recent Changes, and Management
   (D.N. Nettleship)
9. Modelling the Effects of Hunting on Thick-Billed Murres *Uria lomvia* Breeding in Eastern Canada and West Greenland
   (D.N. Nettleship)
10. Population Status and Trend of the Atlantic Puffin *Fratercula arctica* in Newfoundland
    (D.N. Nettleship)
11. Commercial Fisheries and Seabirds - Impact of Food Shortages on Productivity of the Atlantic Puffin *Fratercula arctica*
    (D.N. Nettleship)
12. Reintroduction of the Atlantic Puffin *Fratercula arctica* to Former Breeding Sites in Maine
    (D.N. Nettleship)
13. Monitoring Alcid Populations at Machias Seal Island, N.B.
    (D.N. Nettleship)
14. The Pelagic Distributions of Seabirds in Newfoundland and Eastern Arctic Waters, as Shown by Aerial Surveys
    (R.G.B. Brown)
15. A Gazetteer of the Principal Sites for Breeding and Non-Breeding Seabirds in Atlantic Canada
    (R.G.B. Brown)
16. Investigations of Recent Changes in the Fall Migration Patterns of Red and Red-necked Phalaropes *Phalaropus fulicarius* and *P. lobatus* through the Bay of Fundy
    (R.G.B. Brown)
17. Reduction of Losses of Cultured Mussels to Sea Ducks
    (E.H.J. Hiscock)

B. LIMNOLOGICAL STUDIES OF WATERBIRD HABITATS

1. Kejimkujik LRTAP Studies (Integrated Monitoring) Coordination
   (J. Kerekes)
2. Impact of Acidic Precipitation on Nutrients and Invertebrates
   (J. Kerekes)
3. Monitoring of Piscivorous Birds in the Kejimkujik Watersheds
   (J. Kerekes)

ATLANTIC GEOSCIENCE CENTRE

A. COASTAL GEOLOGY PROGRAM

1. Beaufort Sea Coast
   (P.R. Hill)
2. Coastal Environments and Processes in the Canadian Arctic Archipelago
   (R. Taylor)
3. Coastal Morphology and Sediment Dynamics, Southeast and East Cape Breton Island, Nova Scotia
   (R.B. Taylor)
4. Consulting Advice on Physical Environmental Problems in the Coastal Zone (Based on *Foraminifera* and *Ostracoda)*
   (R. Taylor)

5. Morphology, Sedimentology, and Dynamics of the Newfoundland Coast
(D.L. Forbes)
6. Nearshore Sediments and Non-Fuel Minerals
(G. Fader)
7. Sediment Dynamics and Depositional Processes in the Coastal Zone
(D.L. Forbes)

B. GEOLOGY OF COASTAL INLETS

1. Littoral Investigation of Sediment Properties (LISP) in the Bay of Fundy
(C.L. Amos)
2. Sedflux: On the Transfer of Sediment from Land to the Continental Shelf
(J. Syvitski)
3. Sediment Dynamics at the Head of the Bay of Fundy
(C.L. Amos)
4. Temperature Response of Nearshore Benthonic Foraminifera-Pilot Experiment
(C. Schafer)
5. The Recent Paleoclimatic and Paleoecologic Records in Fjord Sediments
(C.T. Schafer)

C. GEOLOGY OF THE SOUTHEASTERN CANADIAN MARGIN

1. Bedrock and Surficial Geology: Grand Banks and Scotian Shelf
(G.L. Fader)
2. Comparative Studies of the Continental Margins of Canada
(M.J. Keen)
3. Computer-Based Geological Map Compilations-Offshore Eastern Canada
(G. Fader)
4. Engineering Geology of the Atlantic Shelf
(R. Parrott)
5. Facies Models of Modem Turbidities
(D. Piper)
6. Ice Scouring of Continental Shelves
(C.F.M. Lewis)
7. Marine Geotechnical Study of the Canadian Eastern and Arctic Continental Shelves and Slopes
(K. Moran)
8. Stability and Transport of Sediments on Continental Shelves
(C.L. Amos)
9. Quaternary Geologic Processes on Continental Slopes
(D. Piper)

D. EASTERN ARCTIC AND SUBARCTIC GEOLOGY

1. Eastern Baffin Island Shelf Bedrock and Surficial Geology
(B. MacLean)
2. Ice Island Sampling and Investigation of Sediments (LSIS)
(P. Mudie)
3. Near-Surface Geology of the Arctic Island Channels: NOGAP II
(B. MacLean)
4. Quantitative Quaternary Paleoecology-Eastern Canada
(P. Mudie)
5. Quaternary Biostratigraphic Methods for Marine Sediments
(G. Vilks)
6. Surficial Geology, Geomorphology, and Glaciology of the Labrador Sea
(H. Josenhans)
7. Temporal and Spatial Variation of Deep Ocean Currents in the Western Labrador Sea
(C.T. Schafer)

E. WESTERN ARCTIC GEOLOGY

1. Surficial Geology and Geomorphology-Mackenzie Bay, Beaufort Continental Shelf
(S.M. Blasco)

F. GEOCHEMISTRY

1. Diagenesis and Geochemical Cycling
(R. Cranston)
2. Early Diagenesis in Quaternary Marine Sediments of Eastern and Arctic Canada
(D. Buckley)
3. Environmental Marine Geology of Halifax Inlet and Approaches, Nova Scotia
(D. Buckley)

G. REGIONAL GEOPHYSICAL SURVEYS

1. East Coast Potential Fields
(R. MacNab)
2. Interpretation of Potential Field Data
(J. Verhoef)
3. Magnetic and Gravity Anomalies over Sedimentary Basins
(B. Loncarevic)
4. Magnetic Compilations in North Atlantic and Arctic Oceans
(R. MacNab)
5. Ocean Mapping
(R. MacNab)
6. Regional Geophysics of the Mesozoic-Cenozoic of Baffin Bay and Labrador Margin
(A. Edwards)

H. HYDROCARBON RESOURCE APPRAISAL

1. Hydrocarbon Inventory of the Sedimentary Basins off Eastern Canada
(M.E. Best)
2. Interpretation of Geophysical Data from the Scotian Margin and Adjacent Areas as an Aid to Basin Synthesis and Estimation of Hydrocarbon Potential
(B.C. MacLean)
3. Maturation Studies
(K.D. McAlpine)
4. Overpressure Studies of the Offshore Sedimentary Basins of Eastern Canada
(M.E. Best)
5. Sedimentological and Geochemical Studies of Hydrocarbon Reservoirs of Offshore Eastern Canada
(D.J. Cant)

I. BIOSTRATIGRAPHY

1. Biostratigraphic Zonation *(Foraminifera-Ostracoda)* of the Mesozoic and Cenozoic Rocks of the Atlantic Shelf
(P. Ascoli)
2. D.S.D.P. Dinoflagellates
(G.L. Williams)
3. Quantitative Stratigraphy in Paleo-Oceanography and Petroleum Basin Analysis
(P. Gradstein)

J. GEOLOGICAL DATABASES

1. Conversion of AGC Magnetic Tapes to an Archival Medium
(I. Hardy)
2. Geriatric Core Study of the Canadian Eastern and Arctic Continental Shelves
(I. Hardy)
3. Information Database-Offshore East Coast Wells
(G.L. Williams)

4. Palynological Database
(*G. Williams*)

K. GEOLOGICAL TECHNOLOGY DEVELOPMENT

1. Large Diameter Piston Corer Development
(B. MacKinnon)
2. Polar 8 Marine Geoscience Capability Development
(K. Manchester)
3. The Development and Implementation of Remote Operated Vehicle Techniques
(K. Manchester)

L. SPECIAL GEOLOGICAL PROJECTS

1. Basin Atlases-Offshore Eastern Canada
(D.I. Ross)
2. Bedrock Geology of Hudson Bay
(A. Grant)
3. Montagnais Impact Geophysical Investigation
(A. Edwards)
4. Ocean Drilling Program (Planning)
(D.I. Ross)
5. Provision of Scientific Advice to Developing Countries
(D.I. Ross)

M. INVESTIGATIONS OF DEEP GEOLOGICAL STRUCTURES

1. Arctic Ocean Seismic Refraction and Related Geophysical Measurements
(R. Jackson)
2. Comparative Studies of the Continental Margins of the Labrador Sea and of the North Atlantic
(S. Srivastava)
3. Crustal Properties
(M. Salisbury)
4. Geophysical Study of the Gulf of St. Lawrence Region
(F. Marillier)
5. Marine Deep Seismic Reflection Studies-Offshore Eastern Canada
(C.E. Keen)
6. Ocean Drilling Program in the Labrador Sea and Baffin Bay
(S. Srivastava)
7. Regional Geologic and Plate Tectonic History of the Canadian Appalachians
(G. Stockmal)
8. Seismic Refraction-Labrador Sea and Baffin Bay
(R. Jackson)
9. Seismic Studies of Continental Margins and Ocean Basins of the North Atlantic (LASE)
(I.E. Reid)

N. THEORETICAL GEOPHYSICAL MODELLING

1. Rift Processes and the Development of Passive Continental Margins
(C.E. Keen)

O. BASIN ANALYSIS AND PETROLEUM GEOLOGY

1. Compilation of Geoscientific Data in the Upper Paleozoic Basins of Southeastern Canada
(R.D. Howie)
2. Geological Interpretation of Geophysical Data as an Aid to Basin Synthesis and Hydrocarbon Inventory
(A.C. Grant)
3. Lithologic Evolution and Fluid Migration in the Offshore Basins of Eastern Canada
(A. Fricker)
4. Palynostratigraphic Atlases
(R. Fensome)
5. Regional Subsurface Geology of the Mesozoic and Cenozic Rocks of the Atlantic Continental Margins
(J.A. Wade)
6. Sedimentary Basin Evolution of the Continental Margin of Newfoundland, Labrador, and Baffin Bay
(K.D. McAlpine)
7. Stratigraphy and Sedimentology of the Mesozoic and Tertiary Rocks of Atlantic Continental Margin
(L.F. Jansa)

Voyages

This section describes the vessels that the federal Department of Fisheries and Oceans (DFO), Scotia-Fundy Region, operates for the purpose of scientific research and hydrographic survey. It also lists the voyages that these vessels made during 1988 and '89 and the types of research that were conducted. Cruises on vessels not operated by the department but which involved scientific personnel from DFO's Scotia-Fundy Region and DEMR's Atlantic Geoscience Centre are included as well.

In these lists, the following abbreviations are used:

BSB Biological Sciences Branch
CHS Hydrography Branch, Canadian Hydrographic Service
PCS Physical and Chemical Sciences Branch
AGC Atlantic Geoscience Centre
INRS Institut national de recherche scientifique
MALD Marine Assessment and Liaison Division

C.S.S. *BAFFIN*

- The C.S.S. *Baffin* is a diesel-driven ship designed for hydrographic surveying but also used for general oceanography. The ship is owned by DFO and is operated by the department's Scotia-Fundy Region.

- Principal statistics - Lloyds Ice Class I hull . . . built in 1956 . . . length 86.9 m . . . breadth 15.1 m . . . draft 5.7 m . . . freeboard to working deck 3.3 m . . .4,987 tonnes displacement . . . 3,511 gross registered tons . . . 15.5 knots full speed . . . 10 knots service speed . . . 76-day endurance . . . 18,000 nautical mile range at service speed . . . complement of 29 hydrographic staff . . . drafting, plotting, and laboratory space provided . . . Micro-VAX II computer . . . heliport and hangar . . . twin screws and bow thruster for position holding . . . six survey launches.

- In 1988, 248 days at sea and 35,252 nautical miles steamed.

- In 1989, 180 days at sea and 18,585 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
88-002	Apr. 5-19	B. Sanderson, Memorial University	Northeastern Newfoundland, Conception Bay	Biological oceanography, fate of spring plankton bloom
88-009	May 2	J.-G. Dessureault, PCS	Scotian Shelf	DOLPHIN recovery gear trials
88-012	May 9-July 22 Aug. 3-30 Aug. 30-Sept. 30	V. Gaudet, CHS G. Henderson, CHS B. MacLean, AGC	Bay of Fundy, Northwestern Newfoundland, Labrador, Eastern Arctic, Melville Sound	Standard navigation charting, geophysical survey, sedimentology, stratigraphy
88-037	Sept. 30-Oct. 20	C. Ross, PCS	Davis Strait, Scott Trough	Physical oceanography, CTD survey, microbiology near natural oil seeps, sediment traps, moorings

88-039	Oct. 26-Nov. 29	G. Henderson, CHS J. Woodside, AGC	Scotian Shelf	Standard navigation charting, geophysical observations over
	1989			
88-043	Jan. 19-Mar. 18	A. Clarke, PCS Greenland Sea	Norwegian Sea, and CTD survey, International Greenland Sea Project	Physical oceanography, Batfish
89-003	Apr. 18-May 18	T. Platt, BSB	North Atlantic	Primary Productivity, Joint Global Ocean Flux experiment
89-008	May 29-June 23	H. Josenhans, AGC R. Parrot, AGC	Gulf of St. Lawrence Scotian Shelf	Geophysical survey, high resolution seismics
89-014	July 14-19	B. Long, IRNS	Lake Melville, Labrador	Geophysical survey, underwater photography, sediment sidescan, bathymetric mapping, ADFEX project
89-017	July 10-Oct. 6	D. Blaney, CHS	Labrador Sea	Standard navigation charting, geological observations, mooring recovery
89-031	Oct. 16-Nov. 11	G. Rockwell, CHS B. Loncarevic, AGC	Scotian Shelf	Standard navigation charting, geological observations

C.S.S. ***DAWSON***

• The C.S.S. Dawson is a diesel-driven ship designed and used for multi-disciplinary oceanographic research, hydrographic surveying, and handling of moorings in deep and shallow water. The ship is owned by DFO and is operated by the department's Scotia-Fundy Region.

• Principal statistics - built in 1967 . . . length 64.5 m . . . breadth 12.2 m . . . draft 4.6 m . . . freeboard to working deck 1.5 m . . . 2,007 tonnes displacement . . . 1,311 gross registered tons . . . 14 knots full speed . . . 10 knots service speed . . . 45-day endurance . . . 11,000 nautical mile range at service speed . . . scientific complement of 13 . . . 87.3 m^2 of space in four laboratories . . . computer suite . . . twin screws and bow thruster for position holding . . . one survey launch.

• In 1988, 204 days at sea and 26,801 nautical miles steamed.

• In 1989, 163 days at sea and 23,201 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
88-003	Apr. 7-19	E. Levy, PCS	Georges Bank, Scotian Shelf	Investigation of hydrocarbons as nutrients for scallops
88-007	Apr. 25-30	G. Drapeau, INRS	Gulf of St. Lawrence, Magdalen Islands	Nearshore geophysical survey

88-008	May 1-16	J. Syvitski, AGC	Gulf of St. Lawrence	Geophysical survey, sedimentation, seismics, coring
88-015	May 19-27	J. McRuer, BSB	Browns Bank	Juvenile haddock and ichthyoplankton survey
88-017	May 31 -June 3	J. Loder, PCS	Georges Bank	Physical oceanography, vertical and horizontal mixing, tidal front studies
88-019	June 8-21	A. Herman, PCS	Emerald Basin, Banquereau Bank	Primary and secondary productivity of deep basins, comparative fishing with M.V. *Alfred Needler*
88-023	June 23-July 14	N. Oakey, PCS	Georges Bank	Physical oceanography, vertical and horizontal mixing process, tidal front studies
88-025	July 25-Aug. 10	J. Lazier, PCS	Labrador Sea and Shelf	Physical oceanography, moorings
88-030	Aug. 12-19	M. Choquette, Lava1 University	Labrador Shelf, Goose Bay to Lake Melville	Geology, sedimentation
88-032	Aug. 21-31	A. Aksu, Memorial University	Western coast of Newfoundland	Geology, shallow seismics
88-034	Sept. 6-11	B. Johnson, Dalhousie University	Scotian Shelf	Trace metals, particulates
88-035	Sept. 14-25	J. McRuer, BSB	Grand Banks	Capelin larval survey and recruitment study
88-036	Sept. 29-Oct. 17	N. Oakey, PCS	Georges Bank	Physical oceanography, vertical and horizontal mixing
88-038	Oct. 20-31	C. Pereira, Memorial University. K. Moran, AGC	Flemish Cap, Grand Banks	Geology
88-040	Nov. 3- 18	D. McKeown, PCS	Scotian Shelf	Mooring, ship motion, BRUTIV and PARISS tests
88-041	Nov. 23-30	K. Kranck, PCS	Bay of Fundy	Sedimentation studies
88-042	Dec. 3-10	G. Bugden	Gulf of St. Lawrence	Ice forecast and climatological studies
	1989			
89-001	Apr. 4-9	C. Amos, AGC	Georges Bank	Geophysical study of sediment stability and transport
89-002	Apr. 16-27	B. Sanderson, Memorial University	Conception Bay	Physical and biological oceanography, Cold Ocean Productivity Experiment
89-005	Apr. 29-May 1	A. Hartling, PCS	Grand Banks	Mooring deployment and recovery, T-S profiles
89-006	May 4-18	G. Fader, AGC	Northwest Grand Banks	Geophysical study of nearshore surficial and bedrock mapping
89-007	May 20-June 10	G. Vilks, AGC, C. Rodrigues, Univ. of Western Ontario	Gulf of St. Lawrence	Geophysical survey study of bedrock and sedimentation
89-010	June 14-29	D. McKeown, PCS	Scotian Shelf	ROV trials
89-021	July 4-9	B. Johnson, Dalhousie University	Scotian Shelf	Particulates

89-016	July 25 -Aug. 3	C. Fitzpatrick, BSB, Nfld. Region	Labrador Shelf	Annual oceanographic survey
89-024	Sept. 15 - 21	J. McRuer, BSB	Grand Banks	Capelin larval survey and recruitment study
89-028	Sept. 21 - Oct. 4	C. Ross, PCS	Davis Strait	Physical oceanography, mooring recovery and deployment
89-029	Oct. 7 - 22	A. Herman	Scotian Shelf	Primary and secondary productivity of deep basins
89-032	Oct. 27 - Nov. 8	B. Sanderson, Memorial University	Conception Bay	Physical and biological oceanography
89-034	Nov. 10 - 11	P. Yeats, PCS	North Atlantic	Distribution of metal contaminants
89-027	Dec. 19-21	J.-G. Dessureault, PCS	Scotian Shelf	Deployment and recovery of trawl-proof package

M.V. *LADY HAMMOND*

- *The* M.V. *Lady Hammond,* a converted fishing trawler, is owned by Northlakes Shipping Limited and is chartered by DFO specifically for fisheries research. The vessel is operated by the department's Scotia-Fundy Region, and its main user is the Biological Sciences Branch, which has components at BIO, in Halifax, and in St. Andrews, New Brunswick.

- Principal statistics-built in 1972 . . . length 57.9 m . . . breadth 11.0 m . . . draft 4.8 m . . . freeboard to working deck 2.5 m . . . 897 gross registered tons . . . 15 knots full speed . . . 12.5 knots service speed . . . 30-day endurance . . . 8,000 nautical mile range at service speed.

- In 1988, 167 days at sea and 23,198 nautical miles steamed.

- In 1989, 174 days at sea and 24,585 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
88-H183	Apr. 5 - 16	J. Sochasky, BSB	Georges Bank	Live haddock collection for growth experiments
88-H184	Apr. 19 - May 5	E. Dawe, BSB, Nfld. Region	Conception Bay	Crab survey, underwater photography, and trawling
88-H185	May 6-20	B. Nakashima, BSB, Nfld. Region	Grand Banks	Capelin tagging, feeding study
88-H186	cancelled			Unscheduled maintenance
88-H187	cancelled			Unscheduled maintenance

88-H188	June 23-June 30	K. Waiwood, BSB	Scotian Shelf, The Gully	Collection of live halibut for aquaculture trials
88-H189	July 5-21	I. Perry, BSB	Georges Bank	Ichthyoplankton study of tidal front
88-H190	July 26-Aug. 17	E. Laberge, BSB, Quebec Region	Gulf of St. Lawrence	Redfish trawl survey
88-H191	Aug. 22-Sept. 2	G. Harding, BSB	Georges Bank	Lobster larvae vertical distribution
88-HI92	Sept. 5-30	G. Chouinard, L. Currie, BSB, Gulf Region	Southern Gulf of St. Lawrence	Groundfish trawl survey
88-H193	Oct. 3-20	J. Tremblay, BSB	Georges Bank, Southwestern Nova Scotia	Larval scallop survey
88-H194	Oct. 28-Nov. 11	M. Power, BSB	Georges Bank, Browns Bank	Monitoring of resurgence of Georges Bank herring stock
88-H195	Nov. I5-Dec. 3	J. McRuer, BSB	Grand Banks	Capelin larval survey and recruitment study
	1989			
89-H196	May 2-12	B. Nakashima, BSB, Nfld. Region	Conception Bay, NAFO Division 3L	Capelin tagging
89-H197	May 13-23	E. Dawe, BSB, Nfld. Region	Conception Bay	Snow crab survey and gear trials
89-H198	May 24-June 4	D. Taylor, BSB, Nfld. Region	Conception Bay	Snow crab survey
89-HI99	June 5- 11	J. Martell, BSB	Scotian Shelf	Sealworm inventory
89-H200	June 20-29	Y. Delafontaine, BSB, Quebec Region	Gulf of St. Lawrence	Redfish larval survey
89-H201	July l-10	K. Waiwood, BSB	Scotian Shelf, The Gully	Collection of live halibut
89-H202	July 12-30	G. Harding,BSB	Georges Bank	Lobster larval survey, tidal front study
89-H203	Aug. 14-Sept. 3	E. Laberge, BSB, Quebec Region	Gulf of St. Lawrence	Redfish trawl survey
89-H204	Sept. 3-26	G. Chouinard, R. Tallman, BSB, Gulf Region	Southern Gulf of St. Lawrence	Groundfish trawl survey
89-H205	Sept. 28-Oct. 9	J. Martell, BSB	Scotian Shelf	Sealworm survey
89-H206	Oct. 11-21	P. Perley, BSB	Scotian Shelf with ***C.S.S. Dawson***	Juvenile fish trawl survey
89-H207	Oct. 24-Nov. 9	M. Power, BSB	Georges Bank, Browns Bank Georges Bank herring stock	Monitoring of resurgence of
89-H208	Nov. 13-27	A. Fraser, BSB	Grand Banks and recruitment study	Capelin larval survey

C.S.S. *J.L. HART*

- The C.S.S. *J.L. Hart* is a steel stern trawler used for fisheries research, including light trawling operations (bottom and midwater), ichthyoplankton surveys, oceanographic sampling, and scientific gear testing. The ship is owned by DFO and is operated by the department's Scotia-Fundy Region. It is stationed at the St. Andrews Biological Station in St. Andrews, New Brunswick, and conducts most of its work locally, in Passamaquoddy Bay and the Bay of Fundy.

- Principal statistics - built in 1974 . . . length 19.8 m . . . breadth 6.1 m . . . draft 3.65 m . . . 109 tonnes displacement . . . 89.5 gross registered tons . . . 10 knots full speed . . . 8.5 knots service speed . . . 7.5-day endurance . . . 2,000 nautical mile range at service speed . . . scientific complement of 3.

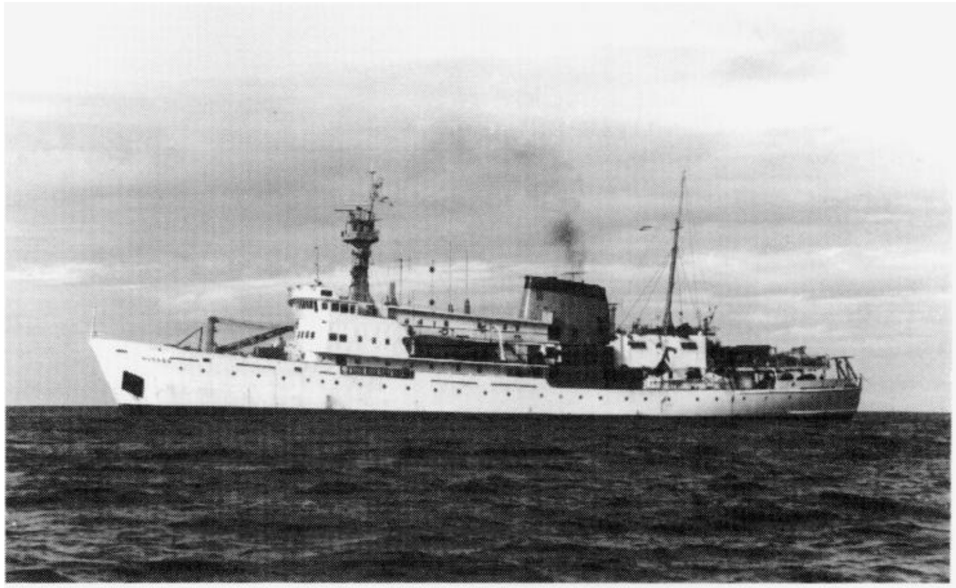
- In 1988, 79 days at sea and 5,357 nautical miles steamed.

- In 1989, 105 days at sea and 9,642 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
88-J049	May 16	J. Gordon, BSB	Bay of Fundy	Herring collections
88-J050	May 24-June 10	J. Gordon, BSB	Bay of Fundy, Gulf of Maine	Juvenile herring survey, joint Canada/U.S. research
88-J051	June 27-July 1	S. Poynton, BSB	Chebucto Head	Live fish collections
88-J052	July 2-9	D. Cairns, BSB, Gulf Region	Southern Gulf of St. Lawrence	Juvenile herring survey
88-J053	July 10-21	J. Murphy, BSB, Gulf Region	Southern Gulf of St. Lawrence	Juvenile cod survey
88-J054	July 27	K. Waiwood, BSB	Bay of Fundy	Live halibut collections
88-J055	July 29	P. Perley, PCS	Bay of Fundy	Live fish collections
88-J056	Aug. 2	D. Wildish, BSB	Bay of Fundy	Phytotoxin monitoring
88-J057	Aug. 4-8	R. Chandler, BSB	Bay of Fundy	Scallop survey
88-J058	Aug. 9	K. Waiwood, BSB	Bay of Fundy	Live fish collections
88-J059	Aug. 11	R. Chandler, BSB	Bay of Fundy	Scallop survey
88-J060	Aug. 22-25, 31	R. Stephenson, BSB	Bay of Fundy	Herring survey
88-J061	Sept. 6 and 13	R. Chandler, BSB	Bay of Fundy	Scallop survey
88-J062	Sept. 20-27	R. Chandler, BSB	Bay of Fundy	Scallop survey
88-J063	Sept. 29	R. Chandler, BSB	Bay of Fundy	Scallop survey
88-J064	Sept. 30, Oct. 7	D. Aiken, BSB	Bay of Fundy	Scallop collections

88-J065	Oct. 11-13	D. Wildish, BSB	Bay of Fundy	Phytotoxin monitoring
88-J066	Oct. 17-18	R. Chandler, BSB	Bay of Fundy	Scallop survey
	1989			
89-J067	Feb. 27-Mar. 1	U. Buerkle, BSB	Bay of Fundy	Acoustic herring survey
89-J068	May 2-26	K. Howes, BSB	Bay of Fundy	Live halibut collections
89-J069	May 30-June 15	D. Gordon, BSB	Bay of Fundy, Gulf of Maine	Juvenile herring distribution
89-J070	June 19-29	M. Lundy, BSB	Bay of Fundy, off Digby	Scallop survey
89-J071	June 4-14	S. Robinson, BSB	Bay of Fundy	Scallop survey
89-J072	July 19Aug. 9	K. Waiwood, BSB	Bay of Fundy	Live halibut collection
89-J073	Aug. 21-25	R. Stephenson, BSB	Bay of Fundy	Herring collections and weir survey
89-J074	Aug. 28-Sept. 2	J. Porter, BSB	Bay of Fundy	Observations of swordfish and tuna fisheries
89-J075	Sept. 5-8	D. Wildish, BSB	Bay of Fundy	Water sampling and coring near salmon aquaculture cages
89-J076	Sept. 11-15	J. Martin, BSB	Bay of Fundy	Phytotoxin survey
89-J077	Sept. 18-Oct. 3	S. Robinson, BSB	Grand Manan	Scallop survey
89-J078	Oct. 5	D. Wildish, BSB	Bay of Fundy	Phytotoxin sampling
89-J079	Oct. 10-27	K. Waiwood, BSB	Bay of Fundy	Live halibut collections
89-J080	Oct. 30-Nov. 3	S. Robinson, BSB	Grand Manan	Scallop survey, underwater camera observations, and gear trials

C.S.S. *HUDSON*



- The C.S.S. *Hudson* is a diesel-electric-driven ship designed and used for multidisciplinary marine science research. The ship is owned by DFO and is operated by the department's Scotia-Fundy Region. The Atlantic Geoscience Centre of the Department of Energy, Mines, and Resources is a major user of this vessel.

- Principal statistics - Lloyds Ice Class I hull . . . built in 1962 . . . length 90.4 m . . . breadth 15.2 m . . . draft 6.3 m . . . 4,847 tonnes displacement . . . 3,721 gross registered tons . . . 17 knots full speed . . . 13 knots service speed . . . 80-day endurance . . . 23,000 nautical mile range at service speed . . . scientific complement of 31 . . . 205 m^2 of space in four laboratories . . . computer system . . . heliport and hangar . . . twin screws and bow thruster for position holding . . . four survey launches.

- In 1988, 140 days at sea and 17,588 nautical miles steamed.

- In 1989, 63 days at sea and 9,801 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
88-001	Apr. 19-May 3	R. Hendry, PCS	North Atlantic, Southern Grand Banks	Physical oceanography, metal distribution, moorings
88-010	Apr. 24-June 9	D. Piper, AGC	Scotian Slope	Geophysical survey, seismics, and coring
88-014	Apr. 5-20	T. Platt, **BSB**	Labrador Shelf, Strait of Belle Isle, Scotian Shelf	Primary and secondary production processes, ground truthing for remote sensing
88-020	June 15-28	B. Loncarevic, AGC	Scotian Shelf	Geological exploration of possible meteor crater
88-022	June 30-July 20	I. Reid, AGC	Gulf of St. Lawrence	Geophysical survey, deep crustal structure
88-024	July 21-Aug. 10	K. Louden, Dalhousie University	Labrador Sea	Geophysical survey, crustal structure, geothermal heat flux
88-026	Aug. 15-Sept. 21	T. Platt, **BSB**	Georges Bank, Sargasso Sea	Biological oceanography at a tidal front, vertical migration of zooplankton and carbon flux
88-029	Sept. 22-26	S. Grant, CHS	Bedford Basin	Electronic chart tests
	1989			
	Sept. 26, 1989-Jan. 2. 1990	Marine Services Division	St. John's shipyard	Mid-life refit

C.S.S. *NAVICULA*

- The C.S.S. *Navicula* is a wooden-hulled fishing vessel owned by DFO. It is operated by the department's Scotia-Fundy Region and is used for research in biological oceanography.

- Principal statistics - built in 1968 . . . length 19.8 m . . . breadth 5.85 m . . . draft 3.25 m . . . 104 tonnes displacement . . . 78 gross registered tons . . . 10 knots full speed . . . 9 knots service speed . . . 8 to 10 hours/day endurance . . . 1,000 nautical mile range at service speed.

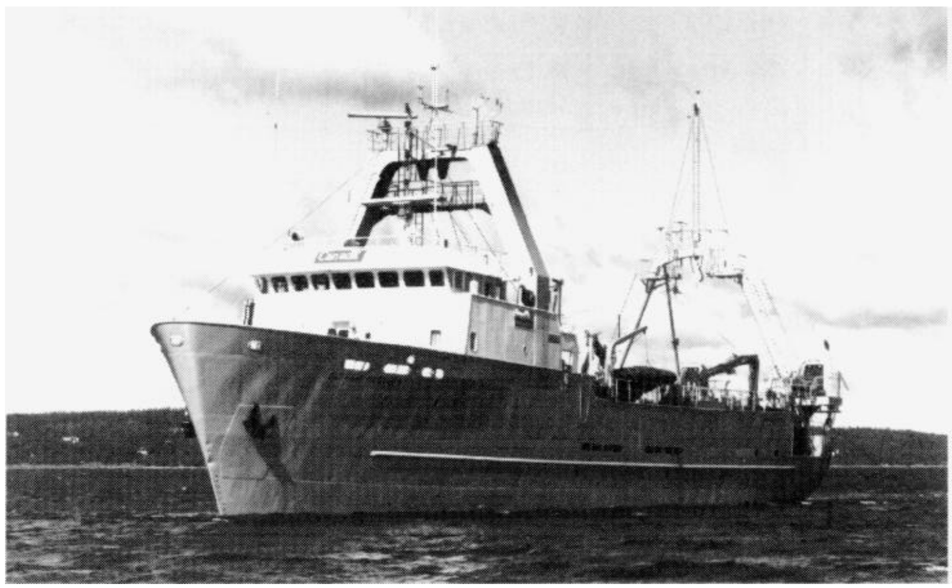
- In 1988, 144 days at sea and 8,209 nautical miles steamed.

- In 1989, 141 days at sea and 8,695 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
88-005	Apr. 19-25 July 6-8,22-27 Sept. 6-12, 20 Oct. 5-7 Oct. 26-Nov. 11	G. Harding, BSB	Ballantyne Cove, St. Georges Bay, Southern Gulf of St. Lawrence	Organochlorine sampling, pollutant concentrations in rainfall and uptake in marine species
88-006	Apr. 26-29 Aug. 27-30	V. Vignier, PCS	Sydney Harbour	Pollution monitoring, physical and biological oceanography, hydrocarbons, PAHs, metals, suspended particulates
88-016	May 24-25	S. Poynton, BSB	Chebucto Head	Live fish collections
88-018	May 28-June 15 June 27-July 5 July 9-22 Aug. 5-24 Sept. 25-Oct. 4 Oct. 8-14	R. Miller, G. Fader, D. Forbes, B. Taylor, AGC	Halifax to Cape St. Mary's, Northumberland Strait, Southwestern Newfoundland, Cape Breton Island	Nearshore surficial geology and mapping using seismics, cores and grabs, support to P.E.I. fixed link development, and mineral/aggregate exploration
88-028	Sept. 13-19 Sept. 21-24	D. Clay, BSB, Gulf Region	Gulf of St. Lawrence	Groundfish distribution study
	1989			
89-009	May 29-June 28	R. Miller, AGC	Halifax Harbour, Bay of Fundy	Surficial geology using seismics to support Halifax Harbour cleanup
89-011	May 11-16 Aug. 3-12 Oct. 21-26	V. Vignier, J. Singh, PCS	Sydney Harbour	Pollution monitoring, winter flounder samples, hydrocarbons, PAHs, metals, suspended particulates
89-012	Dec. 1-2	J. Buckland-Nicks, St. Francis Xavier University	Indian Harbour	*Aplacophora* collection

89-013	July 5-13	T. Landry, BSB, Gulf Region	Miramichi Bay, St. Georges Bay	Sealworm survey
89-015	July 14-Aug. 2	H. Dupuis, BSB, Gulf Region	Southern Gulf of St. Lawrence	Juvenile cod and herring survey
89-019	Nov. 2	R. Addison, PCS	Herring Cove, Halifax Harbour	Live silver hake and flounder
89-020	Aug. 21-28	D. Marcogliese, BSB	Eastern Shore, Cape Breton, Bras D'Or	Benthic survey for sealworm larvae
89-040	Aug. 30-Sept. 14	M. Lanteigne, BSB, Gulf Region	Strait of Belle Isle	Scallop survey
89-026	Sept. 20-Oct. 20	J. Shaw, AGC	Newfoundland south shore	Surficial geology and mapping, coring, seismics

M.V. *ALFRED NEEDLER*



- The M.V. *Alfred Needler* is a diesel-driven stem trawler owned by DFO. It is operated by the department's Scotia-Fundy Region and is used for fisheries research, including acoustics, juvenile fish ecology, and recruitment studies.

- Principal statistics - built in 1982 . . . length 50.3 m . . . breadth 11.0 m . . . draft 4.9 m . . . freeboard to working deck 2.5 m . . . 877 tonnes displacement . . . 925 gross registered tons . . . 13.5 knots full speed . . . 12 knots service speed . . . 30-day endurance . . . 3,000 nautical mile range at service speed . . . scientific complement of 10 . . . contemporary communications systems, electronics, navigational aids, research equipment, and fishing gear.

- In 1988, 235 days at sea and 32,515 nautical miles steamed.

- In 1989, 211 days at sea and 26,038 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
87-N094	Jan. 7-27	C. Dickson, BSB	Chedabucto Bay	Acoustic herring survey
87-N095	Feb. 1-8	M. Showell, BSB	Scotian Shelf	International observer training
87-N096	Feb. 10, 15-26	R. Halliday, BSB	Scotian Shelf and Slope	Deep sea and mesopelagic trawling
88-N097	Feb. 29-Mar. 14	S. Smith, BSB	Georges Bank	Groundfish trawl survey
88-N098	Mar. 22-30	J. Hunt, BSB	Eastern Scotian Shelf	Groundfish trawl survey
88-N099	Apr. 5-14	Y. Simard, BSB, Quebec Region	Gulf of St. Lawrence	Acoustic shrimp survey
88-Nl00	Apr. 18-28	W. Hickey, Fisheries Development Div.	Scotian Shelf	Comparisons of square and diamond mesh

88-N101	May 3-13	W. Smith, BSB	Eastern Scotian Shelf	Haddock tagging
88-N102	May 16-26	P. Ouellet, BSB, Quebec Region	Gulf of St. Lawrence	Shrimp larval survey
88-N103	May 31-June 10	C. Annand, BSB	Scotian Shelf	Pollock survey
88-N104	June 13-28	J. Neilson, BSB	Georges Bank	Juvenile cod and haddock survey, work with *C.S.S. Dawson*
88-N105	July 4-13	P. Koeller, BSB	Western Scotian Shelf, Bay of Fundy	Groundfish trawl survey, SCANMAR observations
88-N106	July 18-27	S. Smith, BSB	Eastern Scotian Shelf	Groundfish trawl survey
88-N107	Aug. 15-Sept. 8	C. Hudon, BSB, Quebec Region	Hudson Strait	Biological oceanography, shrimp survey
88-N108	Sept. 12-29	R. Parrot, AGC	Flemish Pass, Scotian Shelf	Geology
88-N109	Oct. 4-13	P. Hurley, BSB	Scotian Shelf	Redfish trawl survey
88-N110	Oct. 17-27	R. Halliday, BSB	Scotian Slope	Deep sea and mesopelagic trawling
88-N111	Oct. 31-Nov. 24	D. Cairns, BSB, Gulf Region	Southern Gulf of St. Lawrence	Acoustic herring survey
	1989			
89-N112	Nov. 29-Dec. 9	C. Dale, BSB	Scotian Slope	Deep sea and mesopelagic trawling
89-N113	Jan. 6-26	C. Dickson, BSB	Chedabucto Bay	Acoustic herring survey
89-N114	Jan. 3-6	M. Showell, BSB	Scotian Shelf	International observer training
89-N115	Feb. 10-16	J. Martell, BSB	Scotian Shelf	Sealworm inventory
89-N116	Feb. 22-Mar. 7	S. Smith, BSB	Georges Bank	Groundfish trawl survey
89-N117	Mar. 13-21	P. Fanning, BSB	Eastern Scotian Shelf	Groundfish trawl survey
89-N118	cancelled due to ice conditions			
89-N119	Apr. 11-21	C. Dale, BSB	Scotian Slope	Deep sea and mesopelagic trawling
89-N120	May 5-14	W. Smith, BSB	Eastern Scotian Shelf	Haddock tagging
89-N121	May 18-June 2	J. McRuer, BSB	Browns Bank	Juvenile cod and haddock survey, ichthyoplankton survey
89-N122	June 5-15	C. Dale, BSB	Scotian Slope	Deep sea and mesopelagic trawling
89-N123	July 4- 16	P. Koeller, MALD	Western Scotian Shelf, Bay of Fundy	Groundfish trawl survey, SCANMAR observations
89-N124	July 18-27	S. Smith, BSB	Eastern Scotian Shelf	Groundfish trawl survey
89-N125	July 29-Aug. 8	Y. Delafontaine	Gulf of St. Lawrence	Ichthyoplankton (redfish) survey
89-N126	Aug. 9-18	R. Halliday, BSB	Scotian Slope	Deep sea and mesopelagic trawling
89-N127	Sept. 3-14	D. Gascon, BSB, Quebec Region	Gulf of St. Lawrence	Redfish/shrimp trawl gear trials, comparative fishing
89-N128	Sept. 27-Oct. 5	W. Hickey, Fisheries Development Div.	Scotian Shelf	Comparisons of square and diamond mesh
89-N129	Nov. 1-12	D. Cairns, BSB, Moncton	Southern Gulf of St. Lawrence	Acoustic herring surveys
89-N130	Dec. 19-21	P. Koeller, MALD	Scotian Shelf	Trawl-proof package trials and SCANMAR trawl experiment

E.E. *PRINCE*

- The E.E. *Prince* is a steel stern trawler used for fisheries research, including experimental and exploratory fishing and resource surveys. The ship is owned by DFO and is operated by the department's Scotia-Fundy Region.

- Principal statistics - built in 1966 . . . length 39.6 m . . . breadth 8.2 m . . . draft 3.65 m . . . freeboard to working deck 0.7 m . . . 580 tonnes displacement . . . 406 gross registered tons . . . 10.5 knots full speed . . . 10.0 knots service speed . . . 14-day endurance . . . 3,000 nautical mile range at service speed.

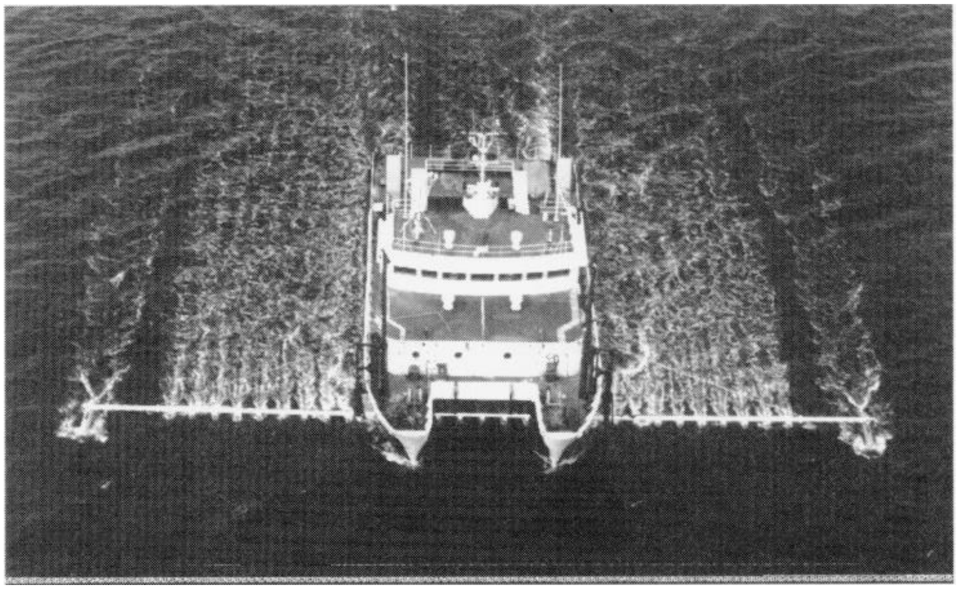
- In 1988, 202 days at sea and 23,973 nautical miles steamed.

- In 1989, 169 days at sea and 19,373 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
87-P363	Mar. 14-24	L. Dickie, BSB	Scotian Shelf	Acoustic groundfish studies, ECOLOG II and BRUTIV tests
88-P364	Apr. 13-15 Apr. 26-27	M. Lewis, BSB	Scotian Shelf Basins	Plankton collection
88-P365	Apr. 28-29	V. Marryatt, BSB	Scotian Shelf	Live cod collection
88-P366	May 4-11	M. Etter, BSB	Eastern Scotian Shelf	Shrimp trawl survey
88-P367	May 16-27	M. Lundy, BSB	Scotian Shelf, Georges Bank	Scallop dredge survey
88-P368	May 30-June 17	R. Dufour, BSB, Quebec Region	Gulf of St. Lawrence	Crab tagging survey
88-P369	June 17-July 6	M. Castonguay, BSB, Quebec Region	Southern Gulf of St. Lawrence, Sydney Bight	Mackerel egg survey
88-P370	July 11-22	T. Rowell, BSB	Eastern Scotian Shelf	Clam tagging, benthic survey
88-P371	July 25-Aug. 11	G. Robert, BSB	Georges Bank	Scallop survey
88-P372	Aug. 17-Sept. 1	W. Hickey, Fisheries Development Div.	Scotian Shelf	Comparisons of square and diamond mesh
88-P373	Sept. 6-16	D. Pezzack, BSB	Georges Bank	Offshore lobster tagging/survey
88-P374	Sept. 19-29	M. Etter, BSB	Scotian Shelf	Shrimp trawl survey
88-P375	Oct. 3 Oct. 4	S. Poynton, BSB M. Power, BSB	Scotian Shelf Scotian Shelf	Live cod collection Plankton gear trials
88-P376	Oct. 6-21	W. Hickey, Fisheries Development Div.	Scotian Shelf	Comparisons of square and diamond mesh
88-P377	Oct. 24-Nov. 10	J. Sochasky, BSB	Bay of Fundy, Gulf of Maine	Larval herring survey

88-P378	Nov. 14	S. Poynton, BSB	Scotian Shelf	Live cod collection
88-P379	Nov. 15-23	J. Martell, BSB	Scotian Shelf	Sealworm/benthic inventory
88-P380	Nov. 29-Dec. 16	M. Chadwick, BSB	Gulf of St. Lawrence	Juvenile herring
88-P381	Mar. 11-18	L. Dickie, BSB	Scotian Shelf	Groundfish acoustics, ECOLOG II tests
	1989			
89-P382	Apr. 11-18	D. Robichaud, BSB	Bay of Fundy	Lobster tagging and distribution survey
89-P383	Apr. 24-May 4	W. Hickey, Fisheries Development Div.	Scotian Shelf, Georges Bank	Comparisons of square and diamond mesh cod ends
89-P384	May 15-25	M. Lundy, BSB	Scotian Shelf	Scallop survey
89-P385	May 29-June 8	T. Rowell, BSB	Scotian Shelf	Offshore clam survey, benthic production studies
89-P386	June 19-July 6	M. Castonguay, BSB, Quebec Region	Gulf of St. Lawrence	Mackerel egg survey
89-P387	July 31 -Aug. 31	G. Robert/ M. Lundy, BSB	Georges Bank	Scallop survey
89-P388	Sept. 5-15	W. Hickey, Fisheries Development Div.	Scotian Shelf	Gear trials with shrimp trawl
89-P389	Sept. 28-Oct. 1	P. Boudreau, BSB	Scotian Shelf/BIO dock	ECOLOG II acoustic trials
89-P390	Oct. 10-18	W. Hickey, Fisheries Development Div.	Scotian Shelf	Selectivity studies of square and diamond mesh cod ends
89-P391	Oct. 24-Nov. 9	J. Sochasky, BSB	Bay of Fundy, Browns Bank	Larval herring survey
89-P392	Nov. 13-Dec. 4	I. McQuinn, BSB, Quebec Region	Northern Gulf of St. Lawrence	Acoustic herring survey
89-P393	Dec. 7-20 (cancelled)	H. Dupuis, BSB, Gulf Region	Southern Gulf of St. Lawrence	Acoustic herring survey

C.S.S. *F.C.G. SMITH*



- The maiden voyage of the catamaran C.S.S. F.C.G. *Smith* occurred in 1986. The ship is owned by DFO and is operated by the department's Scotia-Fundy Region. The vessel is primarily used by the Canadian Hydrographic Service as an acoustic sweep vessel in the coastal areas of the maritime provinces.

- Principal statistics - built in 1985 . . . length 34.8 m . . . breadth overall 14 m . . . single-hull breadth 4 m . . . draft 2.1 m . . . freeboard to working deck 1.3 m . . . 370 tonnes displacement . . . 12 knots full speed . . . 10 knots service speed . . . 7-day endurance . . . scientific complement of 4 . . . integrated sweep transducers, auto-pilot, and laser-ranging positioning system . . . onboard data processing . . . up to 500,000 depth measurements logged daily.

- In 1988, 109 days at sea and 4,894 nautical miles steamed.

- In 1989, 89 days at sea and 4,342 nautical miles steamed.

YEAR & NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
88-004	Apr. 11-22	S. Grant, CHS	Halifax Harbour and Bedford Basin	Electronic chart tests
88-011	May 3-July 22 Sept. 24-Oct. 28	D. Blaney, CHS	Sheet Harbour to Annapolis Basin; Halifax, Pictou, Canso, and Caraquet Harbours	Standard hydrographic sweep surveys of harbours and other inshore areas
88-027	Aug. 8-Sept. 16	N. Doucet, CHS, Quebec Region	Gulf of St. Lawrence north shore	Standard hydrographic sweep survey, exchange with C.S.S. *Louis M. Lauzier*
	1989			
89-004	May 7-June 30 July 23-Sept. 5 Oct. 23-Nov. 3	G. Henderson, CHS	Nova Scotia and Cape Breton coast	Standard hydrographic sweep surveys
89-018	Sept. 5-Oct. 23	R. Sanfaçon, CHS, Quebec Region	Gulf of St. Lawrence	Standard hydrographic sweep survey, exchange with C.S.S. *Louis M. Lauzier*

PARTICIPATION IN OTHER RESEARCH CRUISES

- During 1988 and '89, a number of science organizations in the Scotia-Fundy Region and the Atlantic Geoscience Centre participated in cruises on vessels not operated by DFO, including cooperative research with other countries. These cruises are listed below.

VESSEL / COUNTRY	VOYAGE DATES	CANADIAN PARTICIPANTS	AREA OF OPERATION	OBJECTIVES OF THE VOYAGE
	1988			
M.V. *Skogafoss* (Iceland)	March, June, September, December	F. Dobson, PCS	North Atlantic, Cape Race, Nfld., Reykjavik, Iceland	XBT profiles to define upper-ocean thermal structure
R.V. *Somerset* (U.K.)	April 25-May 9	B. Topliss, PCS	English coast	Collection and groundtruthing of remotely sensed data
Columbus Iselin (U.S.)	Aug. 3-14	K. Kranck, PCS T. Milligan, PCS	Amazon Shelf	AmasSeds Project, sedimentation studies
C.C.G.S. *Nahidik* (Canada)	September	J. Lewis, AGC J. Hunter, AGC	Beaufort Sea	Geophysical survey
C.C.G.S. *Narwhal* (Canada)	Sept. 12-19	H. Josenhans, AGC	Hudson Bay	Multidisciplinary, high-resolution seismics
C.C.G.S. *John A. MacDonald* (Canada)	Aug. 12-Sept. 22	E.J. Comeau. CHS	Griese Fiord, Resolute Passage and Allen Bay, South Bathurst Island (Arctic)	Hydrographic charting
Pholas (Canada)	Sept. 1-Oct. 17	K. Moran, AGC	Grand Banks	Geotechnical properties under Hibernia drill site
S.R.T.M.-K. *Saulkrasty* (U.S.S.R.)	Oct. 17-Nov. 28	C. Bourbonnais, BSB M. Showell, BSB	Scotian Shelf	Juvenile silver hake survey
C.S.S. *Louis M. Lauzier* (Canada)	Aug. 8-Sept. 16	V.J. Gaudet, PCS	Northwest coast of Newfoundland	Hydrographic charting, exchange with *F.C.G. Smith*
	1989			
Casanice (France)	Dec. 25-Jan. 9	D. Piper, AGC	Nice, France	Examination of undersea landslide
M.V. *Skogafoss* (Iceland)	March, June, September, December	F. Dobson, PCS	North Atlantic, Cape Race, Nfld., Reykjavik, Iceland	XBT profiles to define upper-ocean thermal structure
H.M.C.S. *Cormorant* (Canada)	Apr. 21-22 Apr. 27-28	D. Forbes, AGC	Nova Scotia coast	SDL- 1 observations of sediment distribution
H.M.C.S. *Cormorant* (Canada)	Sept. 7-16	S. Blasco, AGC	Barrow Strait	SDL- 1 observations of iceberg scours
C.C.G.S. *Nahidik* (Canada)	Aug. 29-Sept. 21	S. Blasco, **AGC**	Beaufort Sea	Ice scour repetitive mapping program
C.S.S. *Louis M. Lauzier* (Canada)	Sept. 5-Oct. 22	G. Henderson, CHS	Bonavista Bay, Newfoundland	Hydrographic charting, exchange with *F.C.G. Smith*
S.R.T.M.-K. *Maltsevo* (U.S.S.R.)	Oct. 17-Nov. 28	C. Bourbonnais, BSB M. Showell, BSB P. Comeau, BSB	Scotian Shelf	Juvenile silver hake survey

Charts and Publications

Chart production

The Scotia-Fundy Region of the Canadian Hydrographic Service (CHS) has a cartographic staff of 23 and responsibility for 406 nautical charts covering Canada's east coast from Georges Bank to Prince of Wales Strait in the Arctic.

The charts produced by CHS are divided into three types. A New Chart is the first chart to show an area at that scale or to cover an area different from any existing chart. These charts are constructed to the metric contour style in bilingual form using new formats. A New Edition is a new issue of an existing chart showing new navigational information and including amendments previously issued in Notices to Mariners. A Reprint is a new print of a current edition that incorporates amendments previously issued in Notices to Mariners. Reprints for the Scotia-Fundy Region are produced by CHS headquarters in Ottawa.

In addition to the New Charts and New Editions listed below, about one hundred chart amendments and fifteen paste-on patches are issued through Notices to Mariners each year.

1988

New Charts (in-house)

4841 Cape St. Mary's to Argentia
4909 Harbours, Western End of Northumberland Strait

New Charts (by contract)

4117 Saint John and Approaches
4905 Cape Tormentine to West Point
4906 West Point to Baie de Tracadie

New Charts (compiled in-house, drafted by contract)

5049 Davis Inlet to Seniartlit Islands

New Editions (compiled in-house, drafted by contract)

4419 Souris Harbour and Approaches
4483 Caribou Harbour
8006 Scotian Shelf, Browns Bank to Emerald Bank
8007 Halifax to Sable Island, including Emerald Bank and Sable Island

New Editions (compiled in-house, drafted by headquarters)

4529 Fogo Harbour, Seal Cove and Approaches

1989

New Charts (in-house)

4235 Barren Island to Taylors Head
4849 Plans in Conception Bay, Trinity Bay, and Bonavista Harbour
4920 Plans: Chaleur Bay, South Shore
7485 Parry Bay to Navy Channel
7486 Navy Channel to Fury and Hecla Strait

New Charts (by contract)

4911 Entrance to Miramichi River
4912 Miramichi

New Charts (compiled in-house, drafted by contract)

4240 Liverpool Harbour to Lockeport Harbour
4266 Sydney Harbour
4846 Motion Bay to Cape St. Francis
4853 Trinity Bay, Northern Portion

New Editions (in-house)

4201 Halifax Harbour, Bedford Basin
4845 Renews Harbour to Motion Bay
7511 Resolute Passage

New Editions (compiled in-house, drafted by contract)

4842 Cape Pine to Cape St. Mary's
7050 Resolution Island to Cape Mercy

New Editions (compiled in-house, drafted by headquarters)

4047 St. Pierre Bank to Whale Bank
4617 Red Island to Pinchgut Point
4618 Head of Placentia Bay
4620 Come By Chance
4622 Cape St. Mary's to Argentia Harbour and Jude Island

Publications

We present below alphabetical listings by author of publications produced in 1988 and 1989 by the staffs at BIO from the Department of Fisheries and Oceans (DFO), the Department of Energy, Mines, and Resources, and Environment Canada, and by DFO science staff at the Halifax Fisheries Research Laboratory and the St. Andrews Biological Station. Articles published in scientific and hydrographic journals, books, conference proceedings, and various series of technical reports are included. The style and format of these references are as supplied by each unit. For further information on any publication listed here, contact: Marine Assessment and Liaison Division, Department of Fisheries and Oceans, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2. Or call (902) 426-3559.

OFFICE OF THE REGIONAL DIRECTOR, SCIENCE 1988 and 1989

CAMPANA, S., K. FRANK, P. HURLEY, P. KOELLER, F. PAGE, and P. SMITH. 1989. Survival and abundance of young cod and haddock as indicators of yearclass strength. Can. J. Fish. Aquat. Sci. 46 (Suppl. 1): 171-182.

KOELLER, P.A., L. COATES-MARKLE, and J.D. NEILSON. 1989. Feeding ecology of juvenile (O-group) silver hake *(Merluccius bilinearis)* on the Scotian Shelf. J. Fish. Aquat. Sci. 46: 1762-1768.

NICHOLLS, H.B. (ed.). 1989. Investigations of Marine Environmental Quality in Halifax Harbour. Can. Tech. Rpt. Fish. Aquat. Sci. 1693: v+83p.

NICHOLLS, H.B. 1989. Research Advice in Support of Fish Habitat Impact Issues in the Coastal Zone. p. 988-995. In: O.T. Magoon, H. Converse, D. Miner, L.T. Tobin, and D. Clark (eds.). Coastal Zone '89: Proc. of the 6th Symp. on Coastal and Ocean Management. American Soc. Civil Engineers 1, NY.

RICE, J.C., C. .MORRY, T. SEPHTON, G. SEIBERT, S.N. MESSIEH, B.T. HARGRAVE, and R.D. ALEXANDER. 1989. A review of DFO concerns regarding possible impacts of a fixed-link crossing of Northumberland Strait. CAFSAC Res. Doc. 89/16: 44 p.

SEIBERT, G.H., and B. EID. 1989. Vertical Structure of Tidal Currents in Northumberland Strait. (Abstract) Workshop/Symp. on "The Gulf of St. Lawrence: Small Ocean or Big Estuary?", Maurice Lamontagne Institute, Mont-Joli, Quebec, March 14-17, 1989.

SEIBERT, G.H., C.M. MORTON, and A. ISNOR. 1989. Ice Dynamics in Northumberland Strait. (Poster) Workshop/Symp. on "The Gulf of St. Lawrence: Small Ocean or Big Estuary?", Maurice Lamontagne Institute, Mont-Joli, Quebec, March 14-17, 1989.

HYDROGRAPHY BRANCH 1988

BURKE, R.G., S.R. FORBES, and K.T. WHITE. 1988. The C.S.S. F.C.G. Smith-A New and Unique Vessel for the Canadian Hydrographic Service. Proc. of the 11th Int. Hydrographic Conference, Boston, MA, Oct. 1988.

BURKE, R.G., S.R. FORBES, and K.T. WHITE. 1988. Processing large data sets from 100% bottom coverage shallow water sweep surveys: a new challenge for the Canadian Hydrographic Service. Int. Hydrographic Rev. 65(2): 75-89.

O'REILLY, C.T. 1988. Vertical Tidal Datum Control for the Joint American/Canadian Hydrographic Survey of Passamaquoddy Bay/ Grand Manan Channel. p. 124-132. Proc. 1988 ACSM-ASPRS Fall Convention, Virginia Beach, VA, Sept. 1l-16.

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GREGORY, D.N., O.C. NADEAU, and D. LEFAIVRE. 1989. Current Statistics of the Gulf of St. Lawrence and Estuary. Can. Tech. Rpt. Hyd. Ocean Sci. 120: v+176p.

O'REILLY, C.T., S.T. GRANT, and G.O. STEEVES, 1989. The Development of a Permanent Tide Gauge for Remote Areas. p. 208-213. Proc. Canadian Hydrographic Conference, Vancouver, B.C., March 6-10, 1989.

BIOLOGICAL SCIENCES BRANCH

Habitat Ecology Division 1988

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CRANFORD, P.J. 1988. Behaviour and ecological importance of a mud snail *(Ilyanassa obsoleta)* population in a temperate microtidal estuary. Can. J. Zool. 66: 459-466.

GORDON, D.C. (ed.). 1988. An assessment of the possible environmental impacts of exploratory drilling on Georges Bank fisheries resources. Can. Tech. Rpt. Fish. Aquat. Sci. 1633: iv+31p.

HARDING, G.C., and R.W. TRITES. 1988. Dispersal of *Homarus americanus* larvae in the Gulf of Maine from Browns Bank. Can. J. Fish. Aquat. Sci. 45(1): 416-425.

HARGRAVE, B.T., W.P. VASS, P.E. ERICKSON, and B.R. FOWLER. 1988. Supply of atmospheric organochlorines to food webs in the Arctic Ocean. Tellus 40B: 480-493.

JOHNSON, C.R., and K.H. MANN. 1988. Diversity, patterns of adaptation and stability of Nova Scotian kelp beds. Ecol. Monogr. 58: 129-154.

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MACKENZIE, B. 1988. Assessment of temperatures effects on interrelationships between stage duration, mortality, and growth in laboratory-reared *Homarus americanus* Milne-Edwards larvae. J. Exp. Mar. Biol. Ecol. 116: 87-98.

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MESSIEH, S.N., and M. EL-SABH. 1988. Man-made environmental changes in the southern Gulf of St. Lawrence and their possible impact on inshore fisheries. p. 499-523. In: Natural and Man-Made Hazards. D. Reidel Publ., Amsterdam.

MESSIEH, S.N. 1988. Spawning of Atlantic herring in the Gulf of St. Lawrence. Amer. Fish. Soc. Symp. 5: 31-48.

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SILVERT, W.L. 1988. BSIM Beginners' Guide. Internal DFO document: 4 p.

SILVERT, W.L. 1988. BSIM Cookbook Supplement for MS-DOS. Internal DFO document: 4 p.

SILVERT, W.L. 1988. Introduction to BSIM. Internal DFO document: 7 p.

SILVERT, W.L. 1988. The BSIM Cookbook. Internal DFO document: 14 p.

SILVERT, W.L. 1988. BSIM Users' Guide, Ver. 88. Internal DFO document: 14 p.

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SILVERT, W.L. 1988. BSIM Programmers' Manual. Internal DFO document: i+l7 p.

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BOUDREAU, P.R., and L.M. DICKIE. 1989. Biological model of fisheries production based on physiological and ecological scalings of body size. Can. J. Fish. Aquat. Sci. 46: 614-623.

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