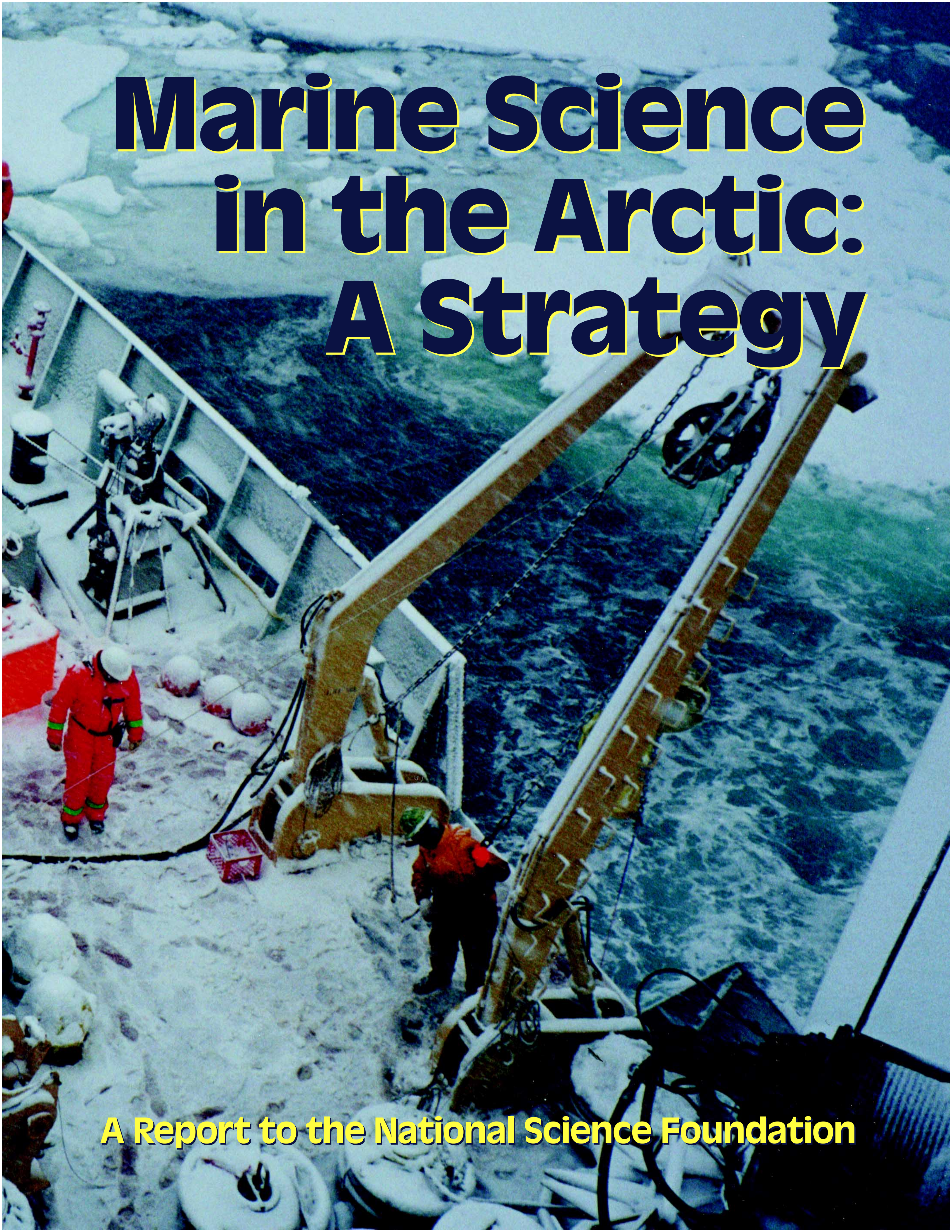
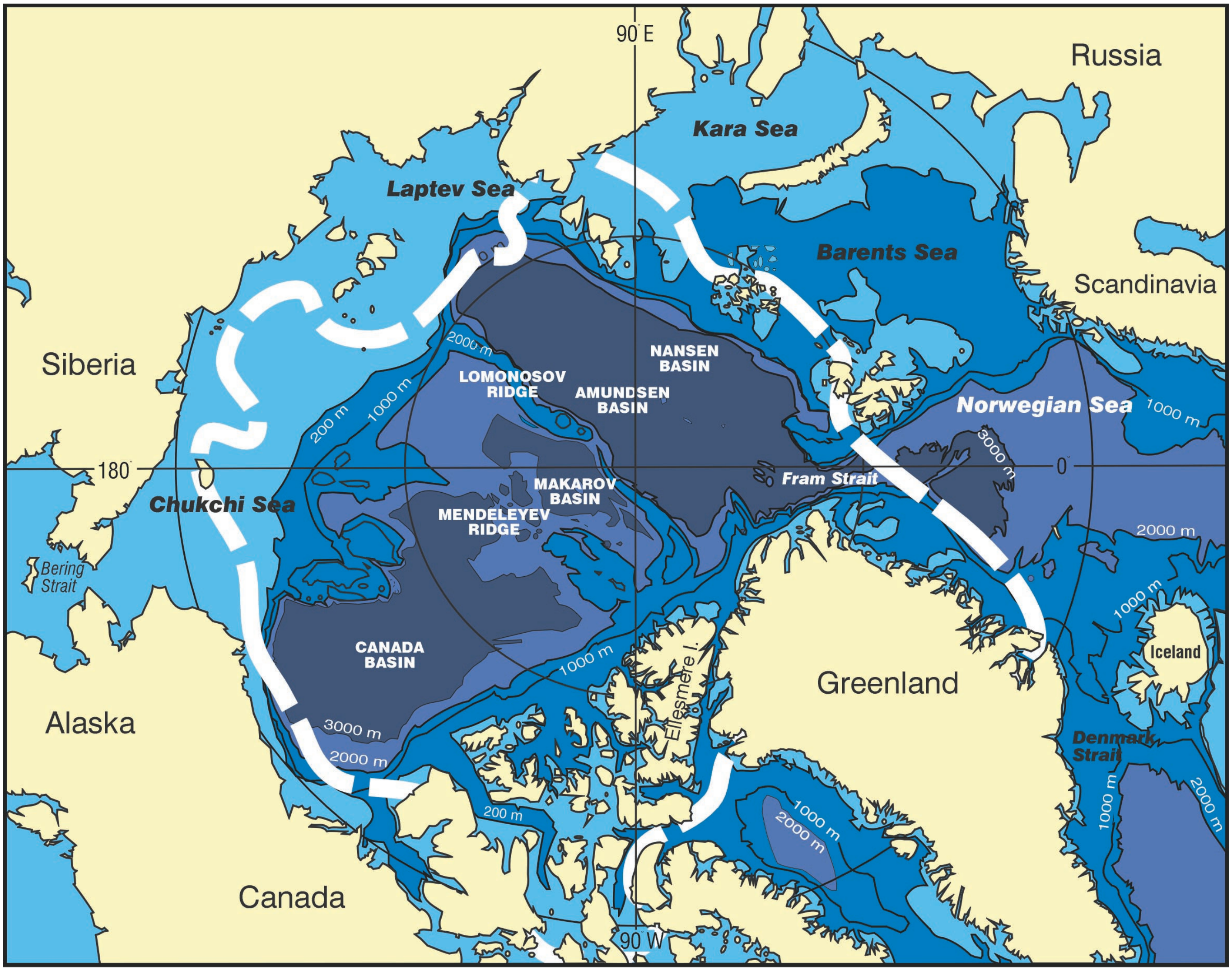
Marine Science in the Arctic: A Strategy



A Report to the National Science Foundation



The Arctic Ocean and adjacent seas. The heavy dashed white line shows average summer ice extent. Courtesy of Robie Macdonald.

Cover photo by Chris Measures. Deploying oceanographic moorings in August in north Baffin Bay on the Canadian Coast Guard ship Louis S. St. Laurent.

Photo on page iii: Surveying sea ice properties during the 1994 Canada-U.S. Arctic Ocean Section. Photo by James Swift.

Marine Science in the Arctic: A Strategy

A Report from the Arctic Research Community to the National Science Foundation

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Foreword

Following the recommendations of a planning group convened by the National Science Foundation in January 1997, the foundation asked the research community for advice and guidance in its long-term planning efforts by preparing a strategic plan for arctic marine sciences. The intent was to provide a grass-roots vision of the next decade of research in the marine Arctic. At the behest of the foundation, and again following the 1997 planning group recommendations, a seven-member working group was appointed through the Arctic Research Consortium of the United States (ARCUS) to develop, in concert with the broader community, the document presented here. A total of three drafts were prepared, and extensive contributions and commentaries from the research community and other interested parties were solicited and received during the entire process.

Much of the work in developing and producing this plan devolved upon Sue Mitchell and Wendy Warnick of ARCUS, and on Clara Jodwalis of the University of Alaska Fairbanks. The working group thanks them warmly!

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Scientific Issues

The marine Arctic has been an integral part of the history of our planet over the past 130 million years and it contributes significantly to the present functioning of the earth and its life. In the Arctic we see signs of variability that suggest the future of the planet may be different from the present and the recent past, for the marine Arctic is intimately involved in global climate and in the earth's great biogeochemical cycles. An adequate understanding of the past and the present Arctic, and of the processes that shape it, is key to predicting the future of this unique region and its impact on society, including its health and commerce.

The National Science Foundation has asked the research community for advice and guidance on how best to deal with these issues of national importance by preparing a strategic plan for basic research in the arctic marine sciences. The emphasis is on major research needs over the next decade, and the perspective is that of the entire marine Arctic viewed in a global context. While this plan is focused on basic research, the applications and benefits of such research are often immediate, and they include matters of special importance to those who live and work in the Arctic.

We consider it likely that much of the scientific research in the marine Arctic during the coming decade will be dominated by five themes, and we believe that the National Science Foundation must be prepared to support that research in an expanded and cohesive program. These five research themes are stated below, together with an explanatory statement and representative major questions that need to be addressed within each theme. Subsequent sections of this strategic plan address each theme in detail.

1. The Arctic in Global Climate

The Arctic is the northern hemisphere heat sink for the earth, and it plays a formative role in both the atmospheric and oceanic circulations.

> *Is the ice cover stable? Under global warming, are the net radiative feedback effects in the Arctic positive or negative? How does the Arctic modulate the global ocean circulation,* e.g., *through its role in the water cycle? Is the Arctic a source or a sink for radiatively active (greenhouse) gases?*

2. Recent Variability and Change in the Arctic

The past decade has seen remarkable changes in the marine Arctic, but we do not know whether these represent temporary perturbations, long-term trends, or new equilibria.

Do recent decreases in ice extent and upper-ocean stratification signal a different sea ice regime? Are anthropogenic (human-caused) signals detectable against the natural variability of the Arctic? What measurements are needed to observe the continuing evolution of the arctic system? How do we acquire a long-term predictive capability?

3. History of the Arctic Ocean

The Arctic Ocean presents the largest gap in the world geologic record, limiting our ability to construct both global tectonic and paleoclimatic models. This gap also limits our ability to exploit the resources of the arctic shelves.

How was the Polar Basin formed? Where are the plate boundaries in the Canada Basin? How does the Gakkel Ridge, the slowest spreading ridge in the world ocean, differ chemically and structurally from other mid-ocean ridges? What does the marine Cenozoic sediment record tell us of past glacial-interglacial transitions, and how does the sediment record compare with the ice-sheet record and the abrupt changes it implies? When did sea ice first appear in the Polar Basin?

4. Biogeochemical Cycles

The global cycles of a variety of materials fundamental to life and to the state of the atmosphere may to a significant extent depend on arctic marine processes.

What is the role of the vast arctic continental shelves in the global cycling of carbon, nitrogen, silicon, and other materials? To what extent does production of biogenic gases within the Arctic contribute to the state of the present global atmosphere? How have changes to the unique arctic environment affected major global biogeochemical cycles, and how might future changes affect those cycles?

5. Health of the Arctic Ecosystem

The arctic ecosystem is adapted to an extreme environment with large seasonal forcing. The system is likely to be severely stressed by changing ice and water conditions, an increase in contaminants, and possibly increased UV radiation.

What is the present productivity of the marine Arctic? Why are there such large variations in the higher trophic levels? To what extent are persistent organic contaminants being sequestered in the arctic food web? How will life on the shelves respond to a changing environment?

Recommendations

Understanding the past and present Arctic is essential to predicting its future and to evaluating the global effects of changes in this unique region.

We therefore recommend that the National Science Foundation:

- Expand support of basic research on the arctic marine system, with particular emphasis on improving predictive capabilities. This emphasis should include both global and regional perspectives, with application to local problems and opportunities.
- Immediately pursue international cooperative agreements for planning and supporting arctic marine science. Canada is a natural first partner with which to initially develop such systematic and sustained cooperation.
- Facilitate scientific access to the Russian exclusive economic zone and continental shelves through a high-level bilateral agreement with Russia.

We further recommend that the National Science Foundation:

- Initiate a program to acquire marine environmental time series, including establishing a marine Environmental Observatory in the Arctic and a set of strategically located repeat hydrographic sections.
- Undertake a program of giant piston coring and support the expansion of International Ocean Drilling Program efforts in the Arctic Ocean.
- Support continued seafloor mapping and integrated geophysical measurements by submarines and other appropriate means.

The National Science Foundation should therefore:

- Initiate a sustained effort to develop instrumentation and measurement techniques suitable for ice-covered seas.
- Seek release from the petroleum industry of geophysical and coring data from the continental shelves.
- Ensure scientific control of expeditionary planning, scheduling, and scientific operation of the *Healy,* in the manner of University National Oceanographic Laboratory System (UNOLS) vessels.
- Use a balanced and complementary logistical system that includes ice breakers, smaller coastal vessels, aircraft, shore support stations, and submarines where feasible.
- Evaluate the logistical needs of arctic research every three to five years. Included in such an evaluation should be the need for a smaller vessel suitable for work in the marginal ice zone.

1 The Arctic in Global Climate

The Arctic Ocean and Global Climate

Two aspects of the interaction between the Arctic Ocean and global climate appear particularly important. The first involves sea ice and the surface heat and mass budgets. The polar regions are the primary global heat sinks, and the Arctic Ocean and its veneer of sea ice are major elements in the global climate system, in part because of the importance of the ice in controlling mass and energy fluxes at the surface.

Considerable effort has been invested in understanding sea ice as a geophysical material, and while the dynamics and thermodynamics of sea ice are probably as well understood as any part of the polar climate system, sizable problems remain. For example, there is not yet a clear understanding of the strong feedback mechanisms within the polar climate system involving ice, clouds, and radiation that is adequate to predict changes in the system under anthropogenic forcing. Furthermore, the state of both the sea ice cover and the thermohaline structure and circulation of the ocean depends on interactions between the ice and the underlying ocean. The ice cover in turn provides a control on the surface heat and mass budgets and thereby on the global heat sink.

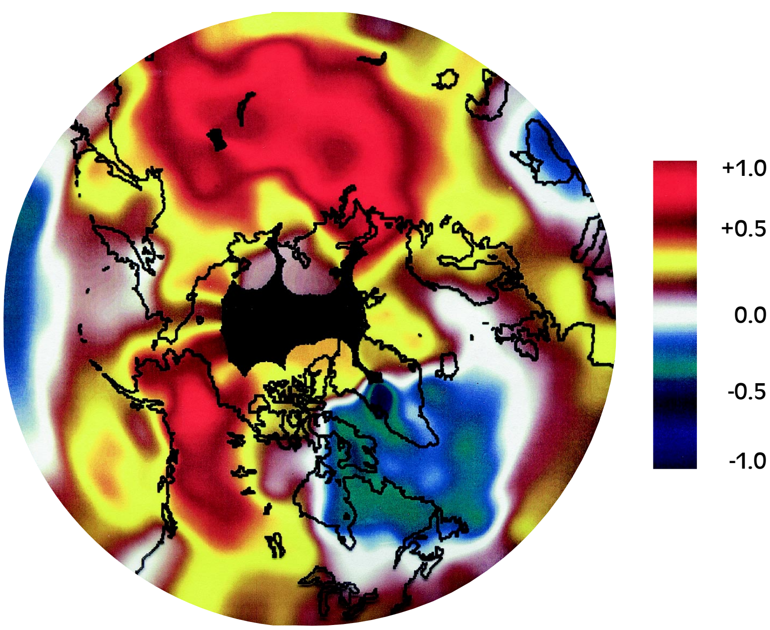
From this perspective, the critical issues relate to how the upper ocean salinity stratification is maintained or altered, for on that depends both the turbulent vertical heat flux from the warm intermediate layer of the Arctic Ocean (which is the largest potential heat source for the ice and surface waters) and the effectiveness of haline convection in stirring the ocean. Indeed, recent changes in the upper Arctic Ocean temperature and salinity structure suggest that this stratification may not be as robust as previously thought, so that both increased vertical heat flux and more effective convective mixing may be realistic prospects, with consequences for the ice distribution.

The second major connection between the Arctic Ocean and global climate that has come to the foreground during the past decade is the oceanic component of the global water cycle. Each year about 3,000 km^3 more sea ice is frozen within the Arctic Ocean than is melted (Aagaard and Carmack 1989; Vinje *et al.* 1998). This surplus of low-salinity ice is largely exported through Fram Strait, and once into the convective

The Arctic Ocean and its veneer of sea ice are major elements in the global climate system.

gyres of the Greenland-Iceland Sea system, it has the potential to influence the overturning cell of the global ocean through a control on the dense overflows that feed the North Atlantic (Aagaard and Carmack 1989; Häkkinen 1993; Delworth *et al.* 1997). Model results (Zhang *et al.* 1998) also indicate an increased Atlantic water inflow to the Arctic Ocean in recent years, particularly via the Barents Sea, which flushes out colder low-salinity arctic water through Fram Strait, which then in turn may influence the overturning cell. An analogous effect may operate in the Labrador Sea, which also receives low-salinity water originally exported through Fram Stait (Dickson *et al.* 1988), as well as waters exiting through the Canadian Archipelago (Belkin *et al.* 1998).

Can variability in these outflows force changes in the global overturning cell? Certainly during the past decade major changes in the convective products of the Labrador Sea (Lazier 1997) and the near shutdown of deep local ventilation in the Greenland Sea (Aagaard *et al.* 1991; Schlosser *et al.* 1991; Boenisch *et al.* 1997) have provided dramatic examples of variable convective forcing within the subpolar gyres, and there is increasing evidence for large variability in the buoyant outflows from the Arctic Ocean. For example, the very large perturbation in freshwater storage in the northern North Atlantic, the so-called Great Salinity Anomaly (Dickson *et al.* 1988) that first appeared in the late 1960s and that appears to have had significant consequences for the water properties of the deep ocean, is thought to have primarily represented increased outflow of sea ice through Fram Strait (Aagaard and Carmack 1989; Häkkinen 1993; Belkin *et al.* 1998). A somewhat smaller freshening event a decade later temporarily stopped the long-term cooling trend in the Labrador Sea by interfering with the convective winter overturn. Indeed, recent suggestions that North Atlantic and Eurasian climate variability may be predictable on decadal time scales rest in part on the variability of such upstream forcing in the Greenland Sea (Griffies and Bryan 1997). Satellite ice tracking suggests that the areal flux of ice through Fram Strait has varied by a factor of 1.6 over the last 18 years, in association with variations in atmospheric forcing (Kwok and Rothrock in press). Longer-term variability can be studied using faunal and isotope proxies recorded in the sediments. Finally, the importance of the oceanic water cycle is increasingly being recognized in other programs concerned with global climate (Schmitt 1995).



Arctic surface temperature trends, 1966–1995, based on annual data. Red and yellow areas have warmed over the past 30 years. Updated from Chapman and Walsh 1993.

Global Climate Model Simulations of Polar Feedbacks

Global climate models project the largest greenhouse warming in the polar regions (*e.g.,* Kattenberg *et al.* 1996). The changes projected over the next 50 to 100 years are large enough that, if realized, they will almost certainly have major impacts on the Arctic Ocean and its peripheral seas. The projected arctic warming involves several feedbacks that are poorly understood, however, particularly related to surface albedo and clouds. For example, large-scale model simulations of polar clouds are seriously deficient (Curry *et al.* 1996), thereby contaminating the simulated radiative fluxes that drive the albedo-temperature feedback. At present, even the sign of the net cloud effect on the surface radiation budget is unknown. The SHEBA program is a step towards remedying the deficiencies in model treatments of interactions between clouds, radiative fluxes, albedo, and temperature, but the primary thrust of SHEBA thus far has been the 1997–98 field program. There remains the challenging task of building upon SHEBA's field program and translating its products into improved large-scale models.

The high-latitude sensitivity displayed by existing climate models has been attributed largely to positive feedbacks involving surface albedo and reduced sea ice extent or thickness (Ingram *et al.* 1989; Rind *et al.* 1995). This attribution may be supported by recent analyses of satellite-derived estimates of ice concentration from 1978 onward that have provided tantalizing hints of a decreasing trend in arctic ice-covered area (Cavalieri *et al.* 1997 and references therein; see also Chapter 2). The principal amplifying feedback depends on the albedo contrast between ice and overlying snow and the underlying ocean, and on the ways in which the albedo varies with surface properties. The feedback may be further enhanced or mitigated by other positive or negative feedbacks, such as those involving clouds. The sea ice albedo feedback mechanism has been investigated in some detail by Curry *et al.* (1995), and its quantification is one of the central themes of the SHEBA experiment (Moritz and Perovich 1996). Nevertheless, representation of surface albedo in the Arctic remains one of the principal challenges to modeling sea ice thermodynamics and is therefore an important source of uncertainty in evaluating the polar amplification of climate change.

A potential source of negative feedback is provided by processes involving sea ice dynamics (the transport and deformation of pack ice). The majority of global climate models used in the 1995 IPCC assessment included only sea ice thermodynamics, with no dynamics. Ice-only model results like those of Hibler (1984), Flato (1996), and Arbetter *et al.* (1997) and the global model results of Pollard and Thompson (1994) indicate that including sea ice dynamics can substantially reduce the sensitivity of a modeled ice cover to perturbations such as might be associated with climate change. Although such experiments are not definitive in terms of the potential role of ice dynamics in altering climate sensitivity, sea ice transport is certainly important in the local freshwater balance at the ocean surface. While the current generation of coupled

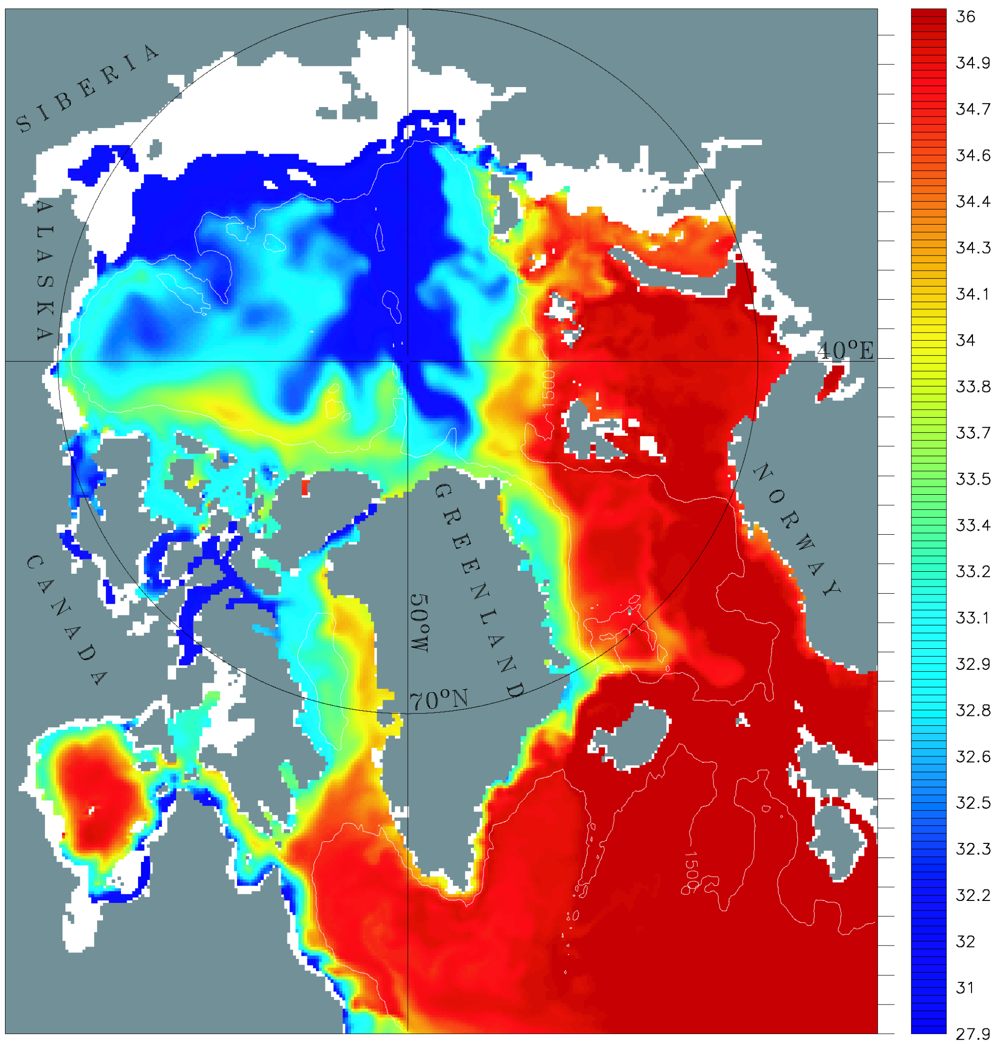
"Global climate changes projected over the next 50 to 100 years are large enough that, if realized, they will almost certainly have major impacts on the Arctic Ocean and its peripheral seas."

> It is the motion of ice, and in particular the transport of ice within the Arctic Ocean and subsequent export, that provide the most important direct connection between ice and the ocean.

climate models is indeed moving toward including some representation of ice dynamics, the level of dynamic sophistication that is required remains unclear. In addition, recent studies (Flato 1996; Holland 1997) indicate that representation of subgrid-scale thickness variability (via the so-called thickness distribution function) can also substantially impact model sensitivity.

An international sea ice model intercomparison project (Lemke *et al.* 1997) is under way to assess existing sea ice dynamic models and gauge their suitability for use in climate studies. In the meantime, dynamic models continue to be developed and refined, with the latest thrust being representation of the mechanical anisotropy associated with preferred direction of ice lead (*e.g.*, Coon *et al.* 1992; Hibler and Schulson 1997).

Whereas surface albedo provides a direct connection between sea ice and the atmosphere that is modified somewhat by ice dynamics, it is the motion



Salinity distribution (in psu) at depth 45–70 m at the end of 1979 after 20-year integration with repeated 1979 atmospheric forcing from the European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis. Inflow of warm and salty Atlantic Water through the Greenland and Barents seas is shown in red and fresh water is in blue. Courtesy of Wieslaw Maslowski (Maslowski et al. *1998).*

of ice, and in particular the transport of ice within and out of the Arctic Ocean, that provides the most important direct connection between ice and the ocean. Indeed, this connection is likely also the principal means by which the Arctic interacts with the global ocean (Aagaard and Carmack 1989). This interaction has become increasingly important as transient climate simulations are done with models that include the three-dimensional ocean general circulation. In this case, the freshwater provided by sea ice exported to the convective regions of the northern North Atlantic can substantially modify the rate at which deep water is formed (and with it the sequestration of carbon) and can also modify the meridional circulation that dominates the northward transport of heat in the Atlantic.

The liquid export of freshwater through both Fram Strait and the Canadian Archipelago is comparable to that exported in the form of sea ice (Aagaard and Carmack 1989). Modeling studies indicate that these flows might oscillate out of phase, possibly influencing whether deep water forms in the northeast or northwest Atlantic (Steele *et al.* 1996). Similarly, model results indicate that the route by which salty waters from the North Atlantic flow into the Arctic might oscillate between two modes (the relative strength of the Fram Strait and the Barents Sea branches), depending on decadal-scale variations of the wind forcing (Zhang *et al.* 1998).

Atmospheric Hydrology and Controls on Upper-ocean Salinity

The large-scale atmospheric circulation contributes to the Arctic Ocean's freshwater anomalies in several ways, including the direct fluxes of precipitation (P) and evaporation (E) at the ocean surface and lateral inputs originating as P and E over terrestrial watersheds. The net terrestrial P-E eventually reaches the Arctic Ocean as river runoff. Over the long term, the Arctic Ocean balances this positive atmospheric influx of freshwater by a net advective export of freshwater (including sea ice) to the North Atlantic. The variability of the various freshwater budget components is poorly documented, however.

The atmospheric freshwater inputs (river runoff and P-E over the Arctic Ocean itself) modify the salinity profile and hence the stratification of the upper ocean. Since the stratification is also affected by other factors, such as advection and the rejection of salt by the freezing of sea ice, the effect of atmospherically induced variations of P and E on the overall salinity budget is not well known. Moreover, the spatial and temporal variations of P and E in the Arctic are notoriously difficult to quantify, confounding attempts to relate interannual to decadal variations of P and E to corresponding oceanic changes.

In order to determine the importance of P and E to the evolution of the upper ocean, both the variations and the

> **The freshwater exported from the Arctic Ocean may modify the northward transport of heat in the Atlantic.**

The increase of arctic precipitation is striking in comparison with the absence of such changes in other latitudes.

means of P and E must be quantified. In the absence of direct measurements, remote sensing and numerical models are candidate tools. In a recent application of remote sensing, P and E have been evaluated from satellite-derived moisture fields and National Centers for Environmental Prediction (NCEP) reanalysis-derived winds (Rothrock *et al.* in press). An independent evaluation of E from winds and ice concentration data allows P to be computed as a residual. Multiyear climatologies compare well with Russian atlas data. Models will likely be most effective if run in a data-assimilation mode, as in the case of the recent atmospheric reanalyses by NCEP, European Centre for Medium-range Weather Forecasting, and NASA. However, the P fields of the NCEP reanalyses contain severe deficiencies (Bromwich and Cullather in press), while the P fields from the other reanalyses appear to be more credible but require further validation.

Adding to the priority of more reliable estimation of arctic P and E is the apparent increase of arctic precipitation during the 20th century (IPCC 1996, Fig. 3.11). The increase of arctic P is striking compared to the absence of such changes in other latitudes. In addition, 20th-century simulations with the ECHAM-4 global climate model, run with time-varying observed SSTs and greenhouse gas concentrations, produce a very similar trend of P in the Arctic (Kattsov in press). If this trend is real, freshwater inputs to the Arctic Ocean have increased substantially during the past century.

Primary needs with regard to the atmosphere-ocean hydrologic linkage are:

- Exploring the potential of obtaining space-time variations of arctic P and E from atmospheric models run in the data-assimilation mode (and incorporating satellite data).
- Using credible ice-ocean models to determine the disposition of P and E anomalies, especially their role in salinity-induced variations of the stratification of the upper ocean.
- Determining the validity of the apparent trend toward greater arctic precipitation during the 20th century and finding the cause of the trend if it is indeed real.

Historical information on arctic precipitation and hydrologic linkages may also be augmented through the traditional knowledge of the indigenous people of the Arctic.

The Arctic Oscillation

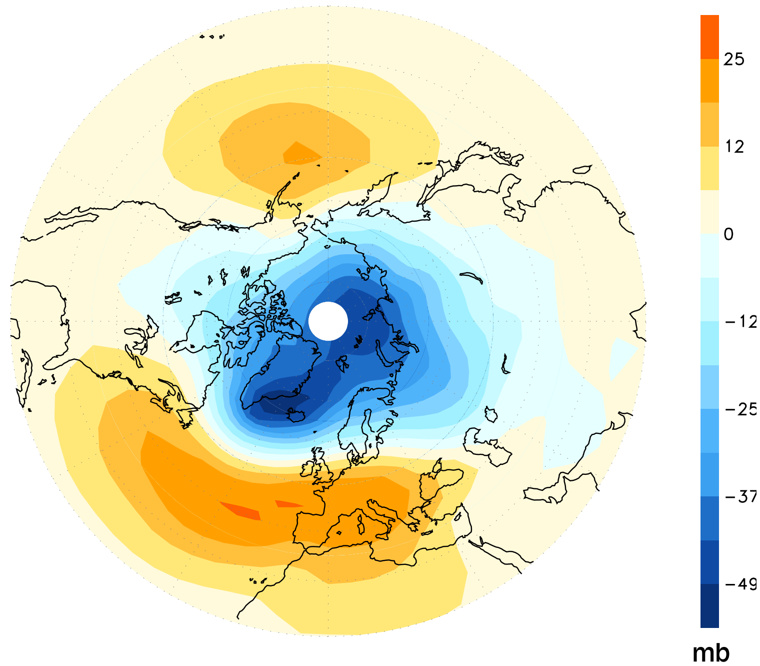
In an ongoing investigation, Thompson and Wallace (1998) have identified a close connection between variations in arctic sea level pressure, lower troposphere temperature, and the strength of the stratospheric polar vortex. This large-scale mode of atmospheric variability, termed the Arctic Oscillation (AO), is centered on the Arctic and extends well southward into the North Atlantic and Pacific. It spans a range of time scales from monthly to interannual, and the well-known North Atlantic Oscillation (NAO) emerges as a subset of this broader mode.

Variations in atmospheric circulation corresponding to the AO have profound implications for the advective fluxes of heat and moisture into the Arctic and for the wind-forced motion of sea ice and the underlying ocean. The periodic strengthening and weakening of the anticyclonic sea ice and ocean circulation described by Proshutinsky and Johnson (1997) appears to be one manifestation of this.

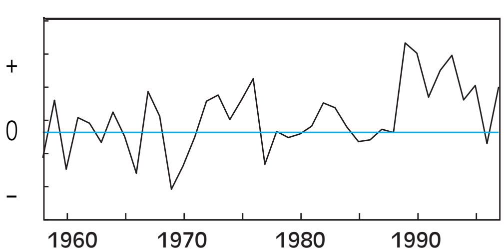
Thompson and Wallace (1998) contend that the recent wintertime warming trend over the northern land areas results from a systematic bias in the AO during the 1990s. The tendency toward lower pressure and weakened anticyclonic circulation noted by Serreze *et al.* (1993; 1999) and changes in the Atlantic layer of the Arctic Ocean described by Swift *et al.* (1997) may likewise be related to this recent phase of the AO. Nevertheless, much research remains to elucidate the mechanisms responsible for the AO and the origin of its low-frequency fluctuations. The immediate questions are whether these variations are driven by changes in the arctic stratosphere or troposphere or by changes at lower latitudes, and whether these changes might be anthropogenic.

Radiatively Active Trace Gases and Aerosols

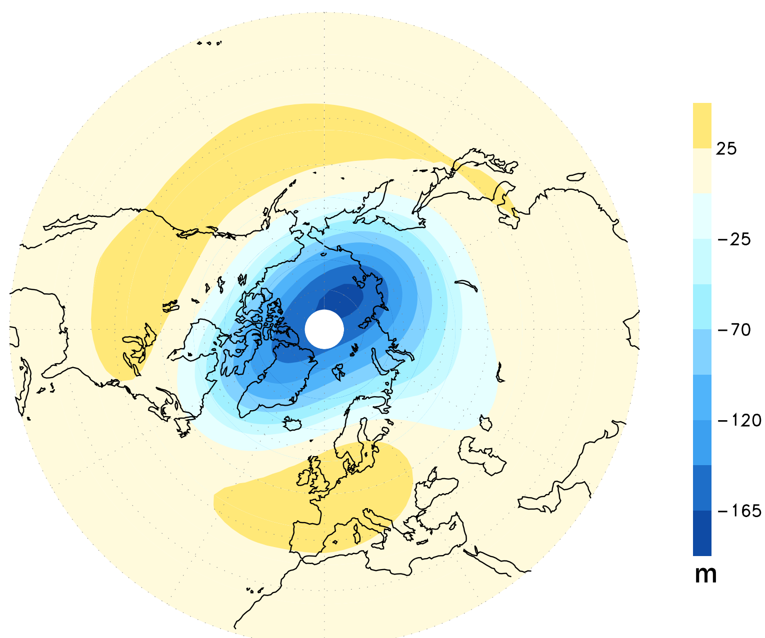
Trace gases and aerosols play key roles in the forcing of arctic climate and climate change. Measurements along the coast of the Arctic Ocean at Barrow



Leading mode of variability in wintertime sea-level pressure 1947–1997.

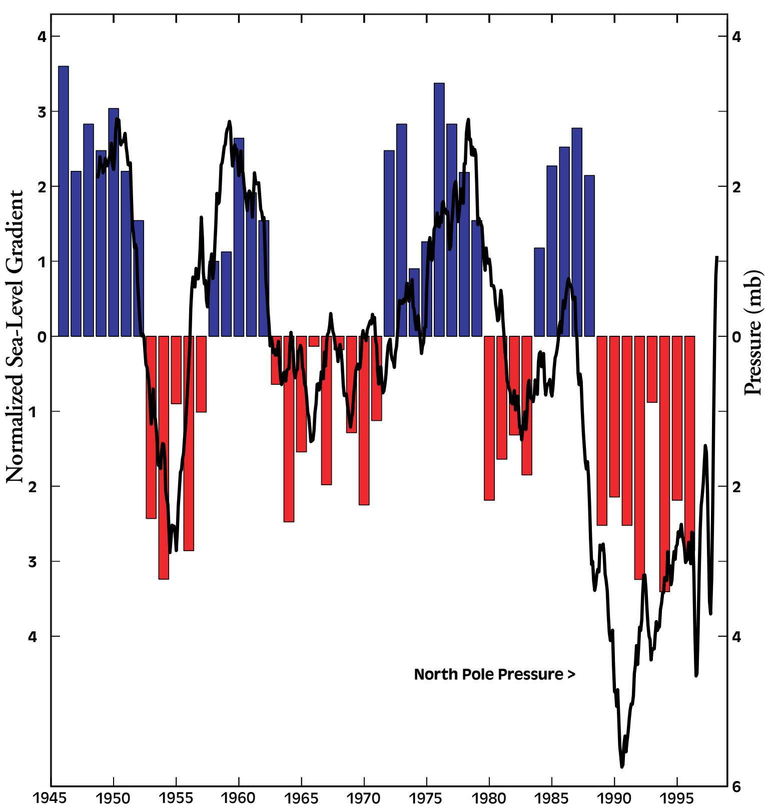


Time series of the Arctic Oscillation corresponding to the spatial patterns shown in the upper and lower panels (right).



Leading mode of variability in 50 mb geopotential height field (a measure of circulation in the stratosphere). The three figures on this page were provided by David Thompson, based on Thompson and Wallace 1998.

show that concentrations of carbon dioxide, methane, CFCs, and other trace gases have increased substantially over the past several decades (Elkins *et al.* 1993; Conway *et al.* 1994; Dlugokency *et al.* 1995). Because these are greenhouse gases, they enhance downward longwave radiation and potentially trigger feedbacks involving arctic surface temperature, surface state, water vapor distribution, and clouds. Feedbacks among these various quantities must be understood and incorporated into climate models if future climate changes in the Arctic are to be predicted with confidence. These feedbacks are summarized by Curry *et al.* (1996).



Time series (blue and red bars) of central Arctic Ocean sea-level gradients from a wind-forced, coupled, ice-ocean model. The sign of the sea-level slope remains constant for four to seven years. Atmospheric sea-level pressure over the North Pole with mean removed (dark line) tracks the sea-level gradients. The increase in North Pole pressure at the end of the record suggests a return to positive sea-level gradients and anticyclonic circulation. Figure courtesy of Mark Johnson, based on Proshutinsky and Johnson (1997).

The importance of atmospheric aerosols, and especially sulfate aerosols, in decade-to-century scale climate change has become apparent in recent years. Globally, the radiative forcing by anthropogenic aerosols is a large fraction of, if not equal to, the present forcing due to greenhouse gas accumulations since pre-industrial times (Barrie 1997). The greenhouse simulations of many climate models now include aerosols in highly parameterized ways. In the context of arctic change, Blanchet (1991) used the Canadian climate model to show that the inclusion of polar tropospheric aerosols equivalent to present levels of arctic haze is sufficient to change a springtime arctic cooling to warming, with consequences for the Arctic Ocean sea ice and surface energy budget. Blanchet and Girard (1995), on the other hand, hypothesized that the dehydration of the arctic atmosphere by anthropogenic aerosols may favor a cooling of the lower troposphere over the Arctic Ocean.

Of particular importance to the Arctic is the forcing by sulfate aerosol particles, which are primary components of arctic haze. Anthropogenic sulfate particles affect the atmosphere through both direct scattering of shortwave radiation and changes in the concentration of cloud condensation nuclei (CCN) that may, in turn, modify cloud formation, cloud lifetime, and the radiative properties of clouds. The aerosol-cloud radiative interactions are difficult to quantify, although it has been determined that 70% of the arctic tropospheric aerosol that is a potential source of CCN is anthropogenic (Li and Barrie

1993). At low aerosol concentrations, the albedo of optically thin marine stratus clouds is especially sensitive to the CCN concentration (Barrie 1997). In addition, an increase of CCN concentration may suppress precipitation and increase cloud lifetime. Arctic marine stratus covers large areas of ice-free portions of the Arctic Ocean and relatively dark (soil-laden or melting) sea ice. Furthermore, the surface energy budget over sea ice in areas of widespread thin stratocumulus is effectively controlled by cloud albedo, so that a change in cloud albedo would be climatically important for the Arctic Ocean.

Of particular relevance to the present discussion is the likelihood that the northern oceans may contribute significantly to the natural atmospheric sulfur budget. Evidence for such a contribution includes the relatively high levels of dimethyl sulfide (DMS) in seawater in northern latitudes (Bates *et al.* 1987; Kettle *et al.* 1996), as well as the high mixing ratios of DMS in the air above the northern oceans (Aagaard *et al.* 1996; Jodwalis *et al.* submitted; see also Chapter 4). However, the high spatial and temporal variability of DMS seawater concentrations, atmospheric mixing ratios, and sea-to-air fluxes make it difficult to quantify the northern oceans' contribution of sulfur to the atmosphere. A quantitative assessment of this contribution is needed, especially since the spatial and temporal gradients imply large variations in the radiative forcing by aerosols over the Arctic Ocean. An additional need is the realistic treatment of atmospheric sulfur compounds and their effects in regional and global climate models. Chemical modules to track the evolution of aerosol species must also be incorporated into climate models. High-resolution regional climate models provide potentially attractive vehicles for testing aerosol parameterizations and chemical modules.

Aerosols may also serve as important hosts for chemical reactions that destroy tropospheric ozone. Recent findings suggest that reservoirs of acidic chlorine and bromine compounds that are inactive in ozone destruction are converted to active chlorine and bromine gases on sulfuric acid aerosols (Barrie *et al.* 1998). This possibility also points to the need for active photochemistry modules in the climate models used to simulate changes in the arctic atmosphere.

Finally, the modeling of arctic trace gases and aerosols will require accurate simulations of the exchanges of aerosols (anthropogenic and natural) and their precursors between the Arctic and middle latitudes. Since the middle latitudes are the sources of most of the anthropogenic gases and aerosols affecting the arctic radiative budget, models must capture the pathways of trace gases and aerosols to the Arctic, as well as their eventual fate in the Arctic.

2

Recent Variability and Change in the Arctic

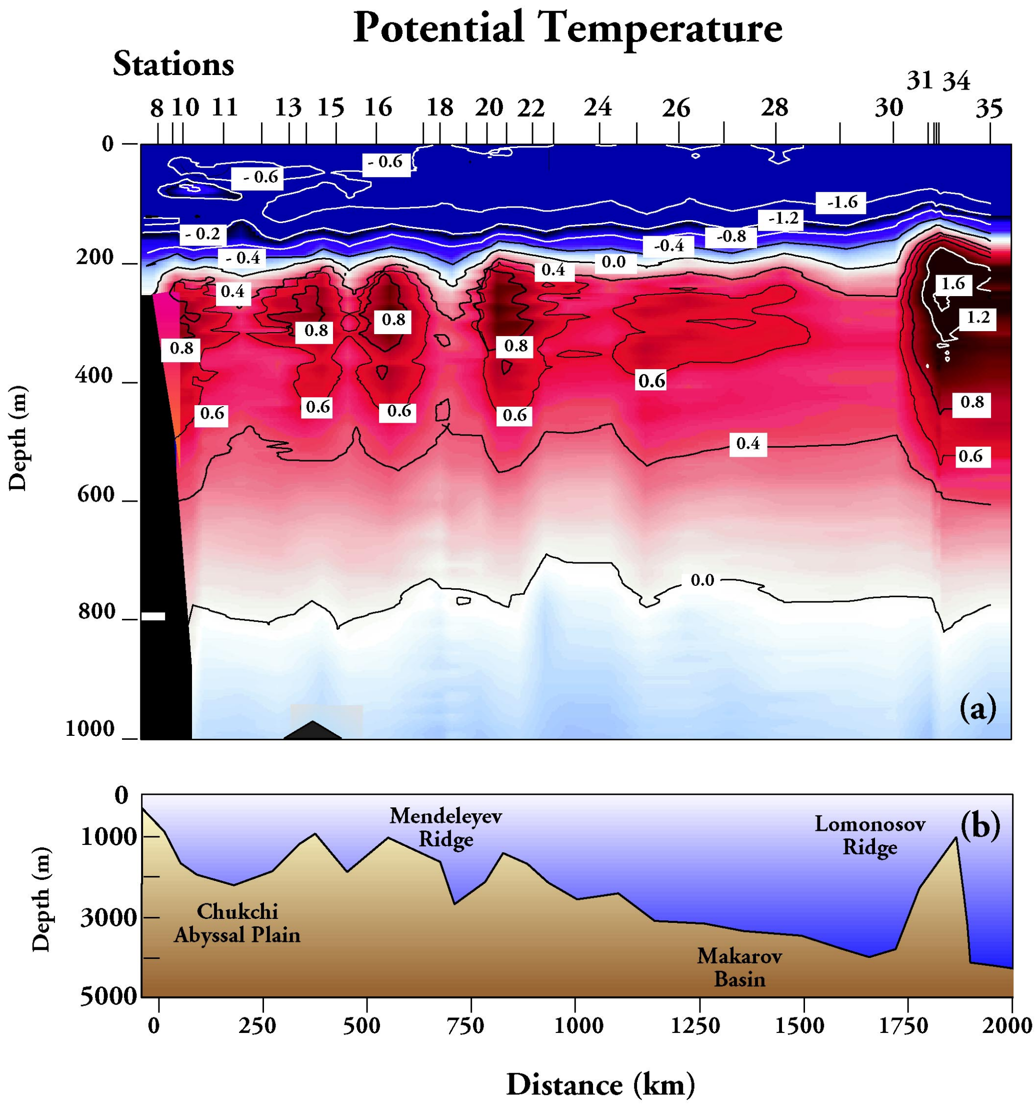
Arctic Variability and Sensitivity

Largely because global warming simulations suggest an amplified climate response in the Arctic, it has been argued that arctic climate provides an early warning of global change (*e.g.,* Manabe and Stouffer 1994; Kattenberg *et al.* 1996). It has also been pointed out, however, that climate variability in the Arctic is large, so that a weak signal-to-noise ratio may initially mask climate trends (Flato 1995; Bitz *et al.* 1996; Steele *et al.* 1996). It seems likely that both the amplified climate response and the large natural variability are connected with the strong feedbacks that characterize the arctic climate system, feedbacks that involve sea ice. In turn, the existence of sea ice depends on a cold, salinity-stratified oceanic substrate.

The past decade has seen a reduction in ice extent within the Arctic Ocean, especially in the Nansen Basin during summer (Cavalieri *et al.* 1997; Steele and Boyd 1998). There have also been large changes in the upper and intermediate layers of the ocean. For example, very recently the mixed layer in the southern Canada Basin has freshened dramatically, while ice thickness has been anomalously low (McPhee *et al.* 1998). The halocline that insulates the sea surface and its ice cover from the warm Atlantic layer of the ocean has thinned over much of the Arctic (Steele and Boyd 1998), and the Atlantic layer has thickened and warmed in the Nansen, Amundsen, and Makarov basins, with a corresponding increase in the vertical temperature gradient between the surface mixed layer and the Atlantic layer (Swift *et al.* 1997; Morison *et al.* 1998).

There have also been other changes with climatic implications. The deep Greenland Sea has continued its multidecadal trend toward warmer and saltier conditions, with a corresponding decrease in oxygen content, reflecting the lack of effective local convection and ventilation (Aagaard *et al.* 1991; Schlosser *et al.* 1991; Dickson *et al.* 1996; Boenisch *et al.* 1997). In contrast, the Pacific inflow to the Arctic Ocean through Bering Strait has freshened in recent years (Aagaard and Weingartner, unpublished data), and the Pacific waters with their characteristic upper ocean temperature/salinity structure and nutrient maxima are now missing from the Makarov Basin (McLaughlin *et al.* 1996; Swift *et al.* 1997; Steele and Boyd 1998).

The atmospheric forcing has also changed, with a dramatic strengthening of the polar vortex [a bias in the AO in the Thompson and Wallace (1998) terminology, as described in Chapter 1]. The reduced surface pressure and increased vorticity in the wind field has likely been accompanied by increased divergence of the ice cover and increases in the large-scale meridional fluxes of atmospheric heat and moisture. Models suggest that the latter changes will have different effects and expression in eastern and western longitudes of the Arctic Ocean (Zhang *et al.* submitted). All in all, there is sufficient evidence to support the view that present conditions in the Arctic Ocean and overlying atmosphere, including adjacent areas in the northern extensions of the North Atlantic, are



The temperature in the upper 600 m in a section from the Chukchi Sea to the North Pole during 1994. The warm core centered near 300 m (upper panel) represents water from the North Atlantic that has been carried by boundary currents along the steep topography (lower panel). The warm cores in the upper panel are as much as 0.6 °C warmer than previously observed. This warming appears related to reduced winter heat loss in the Norwegian Sea immediately upstream of the Arctic Ocean (Swift et al. *1997). Figure adapted from Carmack* et al. *1997.*

Present conditions in the Arctic Ocean and overlying atmosphere, and in adjacent areas in the northern North Atlantic extensions, are unprecedented during this century.

unprecedented during this century. One cannot thereby say that the Arctic is showing the early signs of global warming, but one can say that large changes in ocean circulation and structure, with long time scales, are a reality, and that it would be highly prudent to seek a mechanistic understanding and a prognostic capability.

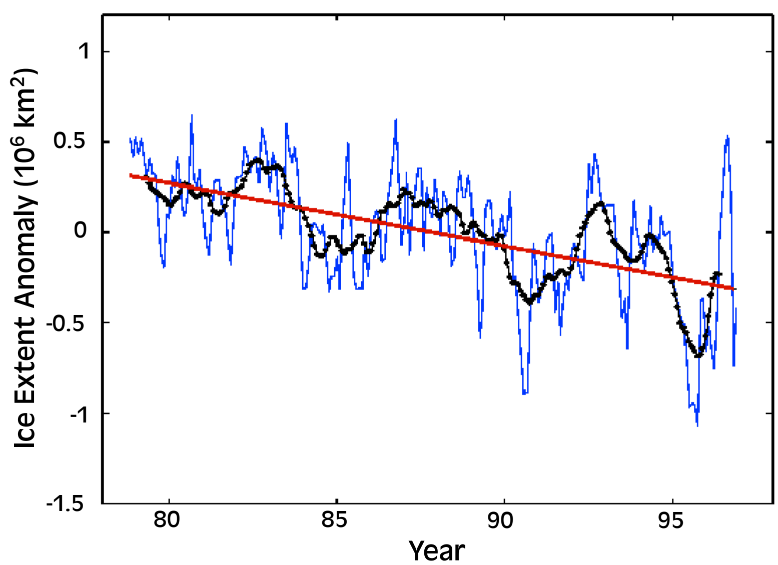
There are also other issues of oceanic environmental sensitivity related to contaminants and pollutants. These include radionuclides, persistent organics, and metals. While radionuclides have received most of the attention, it seems likely that barring catastrophic radionuclide releases, increases in organic loading constitute the more important long-term concern. For example, the arctic seas appear to be concentrating certain persistent organics, an example of the so-called global distillation process, in which the reduced volatilization at low temperatures leads to semi-volatile compounds being preferentially transported into the Arctic (Macdonald and Bewers 1996). While these issues are complex, involving variable atmospheric and oceanic sources, particulate fluxes within the ocean, and the marine food web, the pathways within the ocean are strongly conditioned by ocean circulation and mixing. The ability to predict the evolution of material distributions therefore depends to a considerable extent on improving our understanding of the governing physical processes and their variability.

These various changes in the high-latitude ocean and its ice cover, and in their material burdens, have major implications for the people who live and work in the Arctic, for commerce, for resource extraction, and for marine life. In addition to their global consequences, therefore, the more applied and local implications of such changes argue strongly for acquiring a predictive capability for the arctic marine system.

> The reality of large changes in ocean circulation and structure suggest that we should seek a mechanistic understanding and a prognostic capability.

Sea Ice Variability and Trends

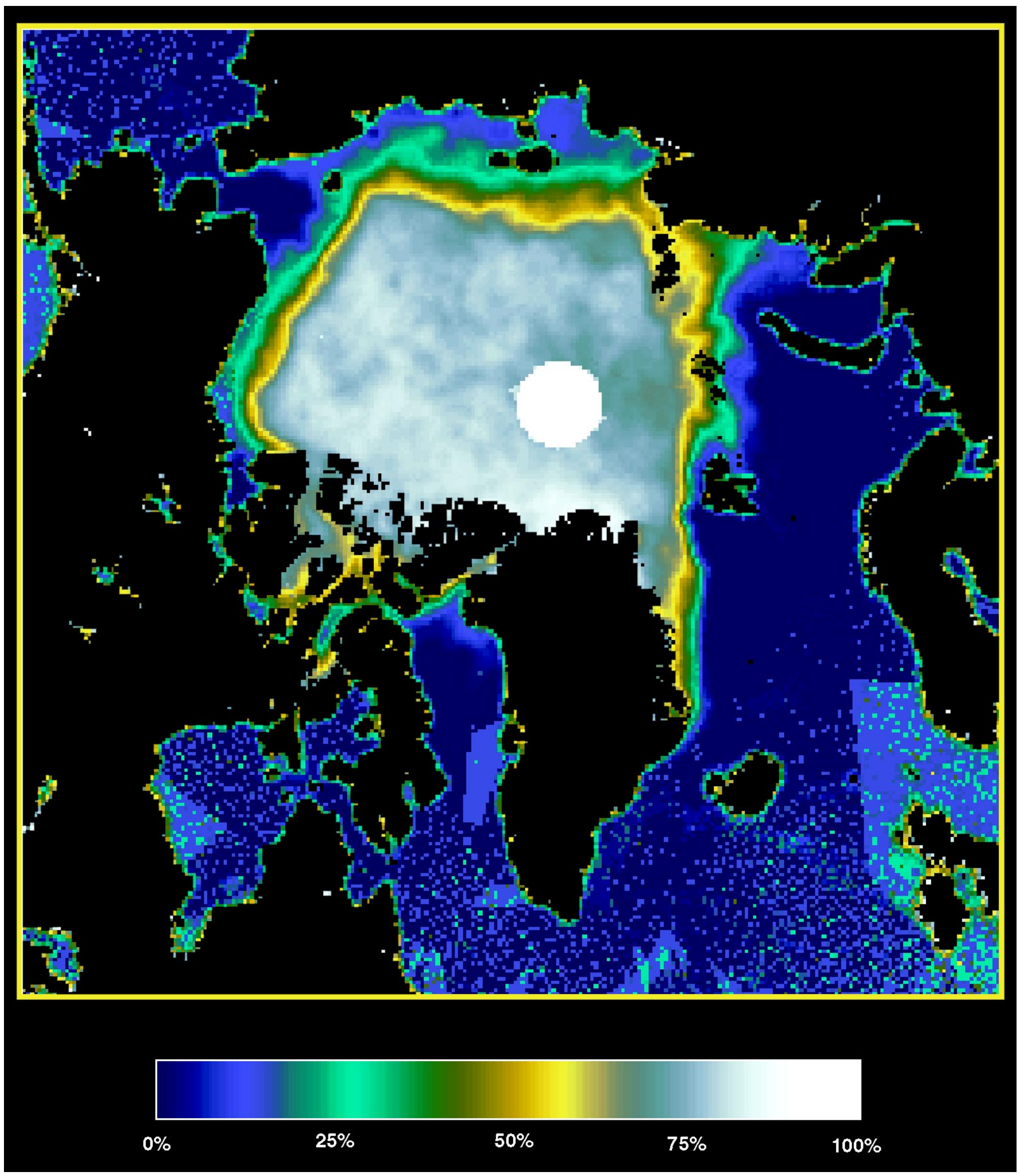
The decrease in sea ice extent of 2.9% per decade since 1980 documented by Cavalieri *et al.* (1997) is statistically significant. Model studies, however, such as those of Häkkinen and Mellor (1990), Flato (1995), and Bitz *et al.* (1996) indicate substantial low frequency variability in the arctic ice cover. Quantifying this background of natural variability is essential if climatically short-term trends such as that described by Cavalieri *et al.* (1997) are to be placed in their proper perspective and if



Departures of sea ice extent from the mean during 1980–1997. The trend of decreasing ice extent (in red) during this period is statistically significant. The blue curve represents monthly ice-extent anomalies, while the black curve indicates a 12-month running mean. Figure provided by D. Cavalieri, based on Cavalieri et al. *1997.*

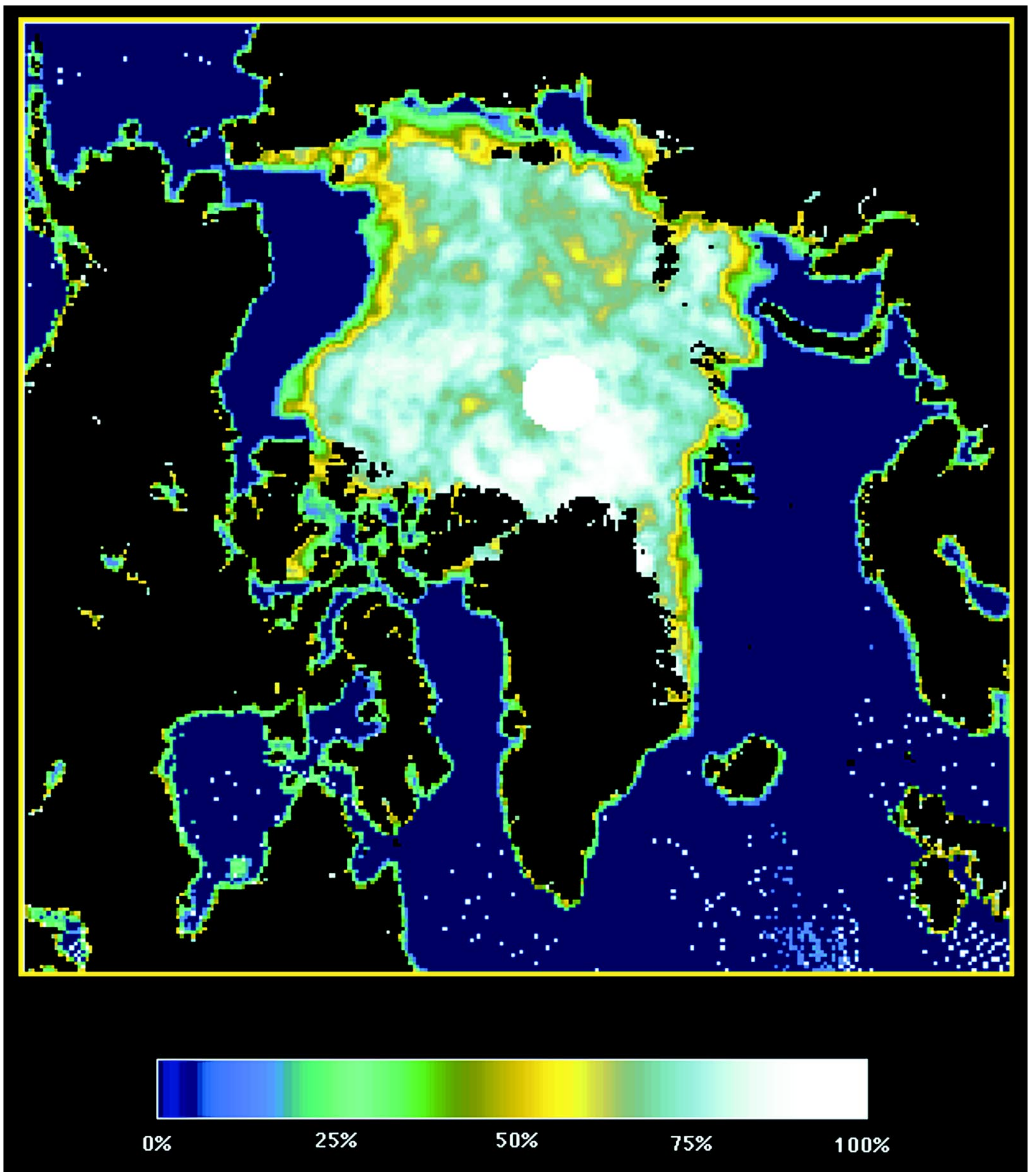
anthropogenic effects on climate are to be tested statistically. Although the satellite record continuously covers only the period since 1978, other sources of instrumental and proxy data may be useful in determining the natural variability of the system. Such proxy data include those embedded in the sedimentary record.

Sea ice variability has further ramifications for climate modeling. Because variability provides insight into the sensitivity of a particular model component, it is a valuable adjunct to the more usual mean-state comparisons between models and observations. Further, the intimate connection between sea ice and polar climate suggests that incorrectly



Ten-year mean concentrations of sea ice on September 30 as obtained from satellite passive microwave measurements. Color bar for concentrations is shown at bottom. Source: NASA National Snow and Ice Data Center, SSMI digital images. Figure courtesy of William Chapman.

specified or modeled variability in the sea ice distribution will lead to unrealistically modeled variability in the coupled atmosphere and ocean. Battisti *et al.* (1997) have recently illustrated this point, showing that simplifications typical of the sea ice component of climate models can indeed artificially reduce variability in ice thickness and thus presumably in other sea ice parameters and their interactions. Identifying the principal processes that control sea ice variability and representing them adequately in global climate models are clearly important challenges for the coming years.

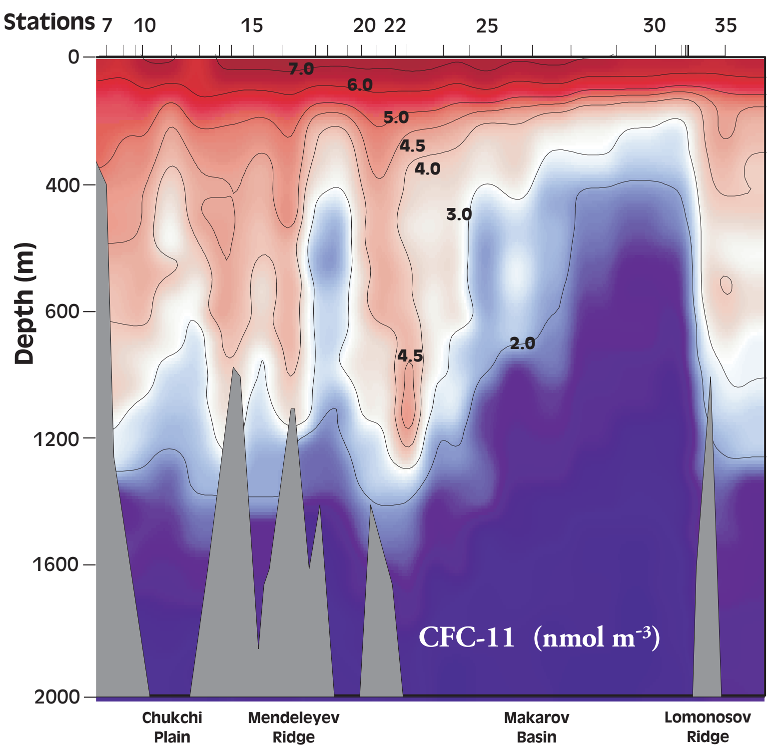


Sea ice concentrations on September 30, 1998, from the NASA National Snow and Ice Data Center, SSMI digital images. Ice concentrations range from 100% (white) to 0% (blue). Figure courtesy of William Chapman.

Tracers have been key to illuminating both circulation patterns and recent dramatic changes in the marine Arctic.

Tracer Results and Variability

Application of water mass tracers has been key to illuminating both circulation patterns and recent climatic changes in the Arctic Ocean and is therefore particularly important in the present context. The distributions of naturally occurring and anthropogenic chemical constituents help define water mass modes and delineate patterns and rates of circulation. For example, the existence of sublayers within the halocline was first revealed through nutrient and oxygen measurements (*e.g.*, Kinney *et al.* 1970; Jones and Anderson 1986), and several attempts to track the origin of these layers have been made on the basis of additional parameters derived from the nutrients and oxygen (Wilson and Wallace 1990; Jones *et al.* 1991; Salmon and McRoy 1994; Rudels *et al.* 1996).



The anthropogenic tracer CFC-11 in the upper 2000 m in a section from the Chukchi Sea to the North Pole during 1994. The deep-reaching fingers of recently ventilated water (high CFC-11 values) represent waters that have sunk from the Barents and Kara seas to mid-depth in the adjacent Arctic Ocean. These ventilated waters are then carried along the steep topography by boundary currents. From Carmack et al. *1997.*

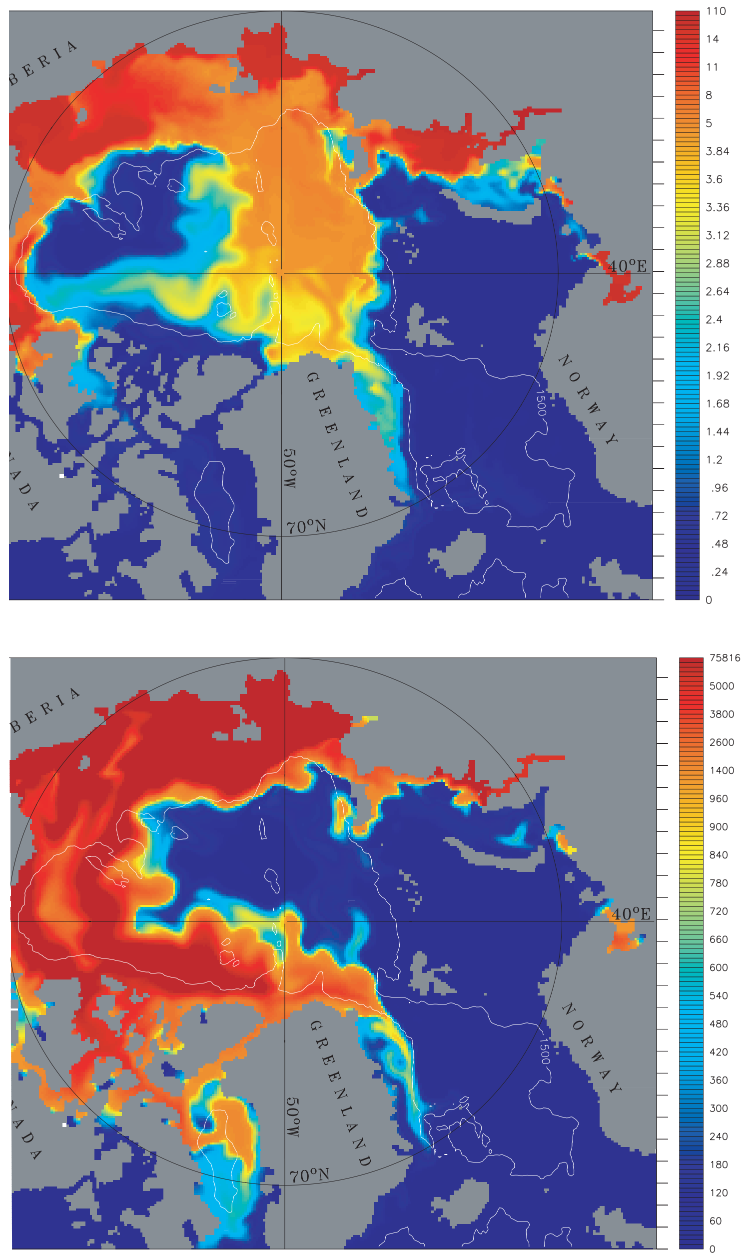
Relationships between nitrate and phosphate have also been exploited to estimate the contributions of Pacific and Atlantic waters to the surface layer (Jones *et al.* 1998). The presence of river water in various interior Arctic Ocean locations has been signaled by relatively high salinity-normalized alkalinity (Anderson *et al.* 1989; Jones *et al.* 1991; Anderson *et al.* 1994) and by ^{228}Ra (Rutgers van der Loeff *et al.* 1995), while more recently, barium distributions have been shown to differentiate the domains of influence of the North American and Eurasian rivers (Guay and Falkner 1997; see also Chapter 4, page 31).

When combined with salinity, and in certain cases other tracers, oxygen isotopes can be applied to the problem of distinguishing between freshening due to sea ice melt and to runoff (Östlund and Hut 1984; Macdonald *et al.* 1989; Bauch *et al.* 1995; Cooper *et al.* 1997). A combination of nutrient and tracer signals has been used to confirm a major shift in the boundary between Pacific and Atlantic water mass assemblies that began in 1989 and moved from the vicinity of the Lomonosov Ridge to near the Mendeleev Ridge (McLaughlin *et al.* 1996).

Naturally and artificially occurring radionuclides and other transient tracers can provide the added dimension of time to the circulation constraints. The chemical signals tend to integrate smaller scale processes and so have been used to estimate average water replacement or ventilation times for marginal seas and the major water masses of the Arctic. Bomb tritium and its decay product ^{3}He, chlorofluorocarbons, ^{39}Ar, and ^{14}C have all been used to assess ventilation and replacement rates over the water column (*e.g.,* Östlund 1982; Wallace and Moore 1985; Macdonald and Carmack 1993; Schlosser *et al.* 1995), and these assessments provide important comparisons with studies based on more conventional physical parameters (*e.g.,* Hanzlick and Aagaard 1980; Becker and Björk 1996).

From these assessments, replacement times are suggested to increase with depth in a manner generally consistent with mass balance considerations and the limited number of measured flow rates. For the surface freshwater layer, replacement time estimates range from a few years in the marginal seas up to a decade in the central Canada Basin. Halocline replacement times appear to be about 5 to 10 years. Complementary information for the Atlantic layer is being provided by the transient tracers ^{129}I and ^{137}Cs, introduced primarily by European nuclear fuel reprocessing plants (Smith and Ellis 1995). Available information suggests that the Atlantic layer waters transit the arctic in a cyclonic boundary current, which may branch in multiple cyclonic loops steered along steep topography within the sub-basins. It appears to take several decades to complete the longest circuit and return to Fram Strait. Deeper waters are renewed on time scales of decades to centuries, with the youngest bottom waters located in the Eurasian Basin (250 to 300 years) and the oldest in the Canada Basin (200 to 500 years).

While these contributions have broken new ground with respect to understanding arctic circulation, the data sets on which they are based are limited both in time and space. Many of the interpretations are based on an assumed steady-state circulation, and up to several



Modeled freshwater in the interval 0–20 m in 1979 (top, with color bar giving percent retention of river mouth characteristics) and 1990–1994 (bottom, with color bar giving freshwater volume per grid cell). In these simulations, the freshwater serves as a tracer of river runoff. Figure courtesy of Wieslaw Maslowski, based on Maslowski et al. *1998.*

It is necessary to complete a first-order characterization of tracer distributions in the Arctic and carry out strategically located repeat sections.

decades of data have been combined to provide sufficient geographical representation to deduce pathways. As more evidence for decadal-scale variability in the Arctic is found, steady-state interpretations come into question. For further progress, it is necessary both to complete a first-order characterization of the tracer distribution in the Arctic and also to carry out a set of strategically located repeat sections and stations that can characterize the variability. Many of the model-dependent ventilation and mixing rate results may have to be revised to account for the evolving understanding of circulation variability, but the existing data nevertheless provide an initial basis for iterative improvement of the rate estimates, and they can guide scientifically and economically sound site selection for further work.

In addition to large-scale shifts of circulation within the Arctic, our understanding of the role of arctic water mass products in global thermohaline circulation has come under renewed scrutiny. It has recently been suggested that the primary source of Denmark Strait overflow water, which along with Iceland-Scotland overflow water ventilates the deep North Atlantic, does not necessarily or exclusively result from local convection in the nordic seas, but rather it may also include Atlantic waters that have circuited the Arctic Ocean at mid-depth to exit with the East Greenland Current (Mauritzen 1996a; 1996b). These waters have properties that fall on a continuum in temperature and salinity between low-salinity surface polar water and recirculating Atlantic water, and so are not recognizable by extrema in the temperature/salinity correlation. They do, however, appear to have distinct tracer properties: arctic Atlantic water has higher ^3He than does surface water, though recirculating waters all have relatively elevated tritium levels (Mauritzen 1996a), suggesting that the recirculating arctic Atlantic water has been isolated from the atmosphere longer than recirculating Norwegian Atlantic Current waters.

Other studies (Bacon 1998) bring into question the constancy of the overflow through Denmark Strait suggested by direct current measurements during the late 1980s and early 1990s (Dickson and Brown 1994). It is essential to understand the origin and variability of this overflow water to correctly construct global circulation models. A similar understanding is required to correctly interpret key oceanic observations. For example, are there tracer signals in addition to ^3He that accompany the cooling and freshening of Atlantic waters as they circuit the Arctic, and do shelf-basin interactions then provide additional distinctive imprints on these waters? These and other questions point to the need for an expanded hydrographic and tracer data base.

3

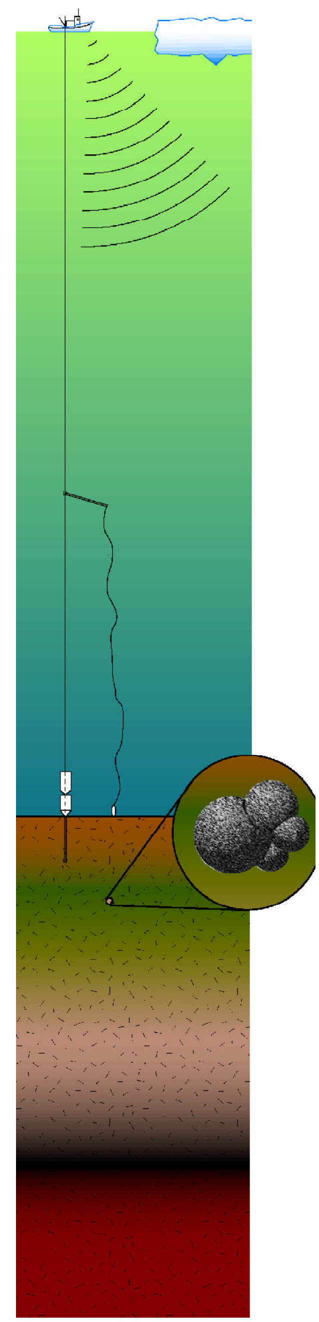
History of the Arctic Ocean

Arctic History in a Global Context

Arctic geologic history is essential to understanding the past and to predicting future change. The present ocean may be quite different from that in the past because of changes in the basin itself, its ice cover, its circulation, and the overlying and surrounding climate. Some processes that operated in the past are now either not active or occur at drastically different rates, *e.g.,* glaciation through marine ice sheets that in the past covered the Barents Sea. Not all of the past changes were slow. Many natural systems operate in more than one mode, with rapid switches between modes when threshold conditions are reached. A dramatic example of this is found in the Greenland ice core record, where about half of the temperature change from the last glacial period is reported to have occurred in less than three years (Severinghaus *et al.* 1998).

The history of the Arctic Ocean should be studied in the context of its global connections. The paleoceanographic and paleoclimatic history of the Arctic is linked to its tectonic evolution. Tectonic control of deep straits such as Fram Strait and eustatic control of shallow water exchanges with the world ocean through the Bering Strait, the Barents Sea, and the Canadian Archipelago, along with the geologic history of the surrounding continents, define the history of the Arctic Ocean and to some extent that of adjacent seas to the south. During most of the Cenozoic, the Arctic Ocean exchanged water with the Atlantic, the Pacific, and surrounding continents. The variation in these fluxes, coupled with changes in sea ice extent and thickness over time, has contributed to the complex history of the Arctic Ocean. Thus, understanding its history will require elucidating the linkages between tectonic, oceanographic, and climatic processes, a multidisciplinary undertaking that is perhaps unique in marine science.

The contrasting tectonic histories of the Eurasian and Amerasian (Canadian) basins present the opportunity to examine the interaction of mid-ocean ridges with continents, micro-plate tectonics, and the sea floor spreading process itself. The ultra-slowly spreading Gakkel Ridge is unique in composition and structure, providing an end member to contrast with other mid-ocean ridges and, where it intersects the Eurasian continent in the Laptev Sea, an excellent example of the interaction between such ridges and continents.



Understanding the history of the Arctic Ocean will require elucidating the linkages between tectonic, oceanographic, and climatic processes.

There are three major research thrusts dealing with and linking these arctic history themes:

- The tectonic history of the Arctic Ocean, focused on such structural features as the ridge complexes.
- The interactions of the Arctic Ocean and its adjacent seas with global environmental dynamics, focused on understanding the earth's changing climate on decadal, millennial, and multimillennial time scales.
- Shelf processes, sediment fluxes, and complex land/sea interaction.

The Arctic has in the past responded quickly and dramatically to environmental change (Polyak *et al.* 1995; Knies *et al.* 1996). The extent to which the Arctic initiates global change is far less clear. Certainly, the establishment of a perennial sea ice cover and changes in its extent and thickness have influenced global climate, but the current sediment archive is inadequate to evaluate the history of the ice cover and its influence on the environment. In order to understand the global evolution of the earth's climate and to predict its future, it is crucial to reconstruct arctic environmental history from multimillennial to decadal time scales (Thiede and Vorren 1994).

The Arctic Ocean is surrounded by the largest continental shelves on earth. Both broad and shallow, these shelves are sensitive to sea-level fluctuations and large seasonal fluvial discharges that influence sea ice cover and depositional environments. These shelves are of great importance to indigenous arctic people and, because of the potential economic resources, probably to the future U.S. economy. The impact of arctic shelves on global change is unknown, but the interplay between sea ice production and export, geochemical and biogeo-

Sampling sediments in sea ice. Photo by Lee Cooper.

chemical fluxes, biota, and sediments is key to understanding the role of these shelves.

Recent Advances and Issues

Despite the large gaps in our knowledge of the history of the Arctic Ocean, significant advances have been made in arctic marine geology and geophysics in the last decade:

- Recognition of the importance of sea ice as a sediment transport agent (Reimnitz *et al.* 1993; Nurnberg *et al.* 1994).
- Determination of sources of ice-rafted debris and paleocurrent patterns (Bischof and Darby 1997).
- Refinement of the marine stratigraphy, especially the use of accelerator mass spectroscopy (AMS) radiocarbon dating for the last 50,000 years (Darby *et al.* 1997).
- Rcognition of rapid changes in paleoclimate and collapse of large ice sheets as indicated by Heinrich layers in the North Atlantic (Bond *et al.* 1992).
- Definition of the nature and extent of Late Weichselian ice sheets over the Barents and Kara seas (Forman *et al.* 1996).
- Recent aeromagnetic and aerogravity surveys and seismic sections in the Arctic Ocean that along with expanded submarine capabilities for collecting acoustic data will advance our understanding of the basic structure and origin of the Arctic Ocean.
- Discovery of large gravity anomalies along the Gakkel Ridge axis that appear to indicate the inhibition of basaltic melt production at spreading rates below 1.3 cm/yr (Coakley and Cochran 1998).

However, our overall understanding lags far behind that of marine geology and geophysics in other oceans. Basic questions such as whether the Arctic Ocean is a harbinger, an amplifier, or merely a passive recorder of climatic change; the onset and long-term variability of the perennial ice cover; and the tectonic evolution of the Arctic Ocean basins remain unanswered several decades after originally having been raised. The primary reason for this is the logistical impediment to collecting adequate geologic samples and data, such as giant piston cores, deep-sea drilling cores, and most geophysical measurements. Yet, recent piston coring and seismic efforts on the Northwind Ridge, and both piston and box coring on the 1994 Arctic Ocean Section have shown that the cores and data collected by these conventional methods can provide new and valuable insights into the pressing unresolved questions about this ocean (Darby *et al.* 1997; Phillips and Grantz 1997; Grantz *et al.* 1998).

The Role of the Arctic Ocean in Global Change

Understanding abrupt climate changes during the past 100,000 to 300,000 years is essential to understanding present climate and to modeling the future. Fundamental in addressing these issues is the sediment record of past changes (Broecker *et al.* 1990). There are clear indications of climatically induced changes in sedimentation, as well as in biotic and chemical proxies,

> The study of multiple climate parameters and their sediment proxies will be essential to establishing the role of the marine arctic in climate change.

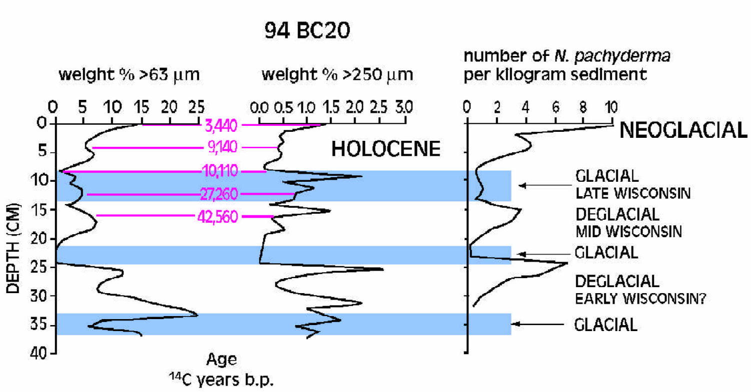
> The Arctic Ocean contains the largest continental shelves in the world, and these shelves have potentially vast reserves of petroleum and mineral resources.

and in the ice-rafted debris distribution in Arctic Ocean sediments (Clark *et al.* 1980; Mudie and Blasco 1985; Darby *et al.* 1997). Linking these records to paleoceanographic and paleoclimatic events recorded in sediment and ice cores that exhibit the global climate history has been hindered by the limited resolution and lack of continuity in the chronostratigraphic record of the Arctic Ocean. The precise timing of changes is critical in determining the role of the arctic in global change. New approaches to direct dating of sediment cores are needed for the time interval beyond the limit of radiocarbon dating (~50,000 years) to the time of the last universal geomagnetic reversal at 780,000 years (Berger and Jones 1996).

The study of multiple climate parameters and their sediment proxies will be essential to establishing the role of the Arctic Ocean and adjacent seas in climate change on both local and global scales. There has never been a coordinated effort to study all of the important sediment proxies (sedimentologic, paleontologic, and geochemical) for paleoceanographic and paleoclimatic changes in the same Arctic Ocean cores. This should be done whenever feasible, rather than conducting sporadic investigations of one or two parameters. In addition, every attempt should be made to link paleo-marine studies in the Arctic to the goals of the global change programs such as Marine Earth System History (MESH) and Arctic System Science (ARCSS).

Regrettably, cores larger than a few centimeters in diameter and from areas of the arctic with sedimentation rates above 1 mm per 1,000 years are rare. All of the T-3 cores collected in the 1960s and early 1970s are 3 cm in diameter, and these constitute more than 90% of the available Arctic Ocean cores (Darby *et al.* 1989). A concerted effort needs to be made to collect large diameter (>15 cm) giant piston cores or deep-sea drilling cores in areas where the sedimentation rates are higher than in the central basin. The Northwind Ridge area has sedimentation rates approaching 8 cm per 1,000 years (Phillips and Grantz 1997), and parts of the continental slope might have even higher sedimentation rates. Cores from these areas will provide the necessary resolution in the geologic record, not only to reveal subtle climatic and paleoceanographic changes but also to correlate these to established high-resolution records in other oceans. The broad shelves in the Arctic also contain areas of high sedimentation during the Holocene, but most sediments on these shelves were eroded during the last glacial interval, when lowered sea levels exposed these shelves or ice sheets occupied them (Elverhøi *et al.* 1989).

Submarines are crucial to expanding the arctic core collection because they



Data from a boxcore taken in the Wrangel Abyssal Plain of the central Arctic Ocean showing rapid change in the Arctic. The two left-hand curves show past changes in ice rafting, and the right-hand curve shows variable foram productivity (adapted from Darby et al. *1997).*

are, without doubt, the best platforms from which to conduct acoustical surveys essential to locating coring sites (Pyle *et al.* 1998). The continental slopes in most of the Arctic Ocean should be reachable by the *Healy* or comparable ice breakers that will be needed for such coring. The prospects for finding high sedimentation rates in the central Arctic Ocean, other than turbidite sequences in the abyssal plains, are remote. The box cores from the 1994 Arctic Ocean Section have revealed rates of >1 cm per 1,000 years throughout the central Arctic for the Holocene and intervals of rapid collapse of ice sheets in North America and elsewhere (deglaciation events) (Darby *et al.* 1997). While these rates do not permit century-scale resolution, they could provide sediment records with millennial-scale resolution if bioturbation is minimal (Clough *et al.* 1997). Because the abundances of foraminifera and other biotic proxies are commonly low in arctic deep-sea sediments, large-diameter cores are essential in order to recover adequate numbers of specimens in as thin a sample interval as possible.

Preparing to send a giant box corer to the bottom of the Arctic Ocean. These cores provide relatively undisturbed sediment samples of the upper 50 cm of ocean bottom. Photo by Lisa Clough.

> Indirect indicators of sea ice cover on the shelves can be found in the ice-rafted debris transported by sea ice.

Land and Shelf Interaction and Sediment Fluxes

The arctic shelves receive and interact with discharges from rivers carrying 10% of the global discharge. Some of these rivers also carry significant contaminant burdens, and the history of anthropogenic pollutants is most likely recorded in the marginal marine and shelf sediments. The impact of changes in these anthropogenic fluxes should also be recorded in the biogenic sediment archives (fossils and biochemical proxies).

Reconstructing the Holocene sedimentation history on the shelves will also facilitate understanding of the history of riverine discharge that plays an important role in maintaining the low-salinity surface layer in the Arctic Ocean, and thus the sea ice cover.

The sediment flux onto and across the arctic shelves and slopes, both present and past, is an important part of the sediment budget in the Arctic, because the central Arctic Ocean has much lower deposition rates than the shelves and slopes. Much more research on sediment fluxes across all arctic shelves needs to be undertaken in order to understand the variability in processes among the different parts of the Arctic (Andrews and Syvitski 1994; Lubinski *et al.* 1996; Polyak and Mikhailov 1996).

Sediment transport via sea ice has also been shown to be important, perhaps even the most important process today (Reimnitz *et al.* 1998). We still understand very little about how sea ice entrains and disperses sediment, however, whether now or in the past, and how variable these processes are.

Sampling dirty sea ice off Prudhoe Bay during the winter of 1978–79. That year, suspension freezing on the shelf entrained 16 times as much sediment as carried by all of the rivers in this area. Photo by Erk Reimnitz.

Permafrost is an important and unique aspect of the arctic coastal zone and even of some offshore areas. The impact of the onset of permafrost and of temporal variations in its thickness and extent are unknown. Whether the climatic changes seen over the last 15,000 to 20,000 years in different arctic land and shelf areas were synchronous is also uncertain. This has direct impact on understanding the nature and cause of climatic change in the Arctic. Even over the last 50 years, some glacier termini have retreated rapidly while others have changed little. Also, little is known about the source and conditions of snow accumulation that eventually lead to ice sheets on arctic land or marginal marine areas.

Because the shelves are the primary areas in the Arctic for sea ice formation, understanding and predicting ice production and export from the Arctic Ocean, along with its potentially important role in global climate, depend on a better understanding of the interaction of the factors involved, such as river discharge, ocean currents, and winds. The sedimentary archive records the history of sea ice over the different shelves and should therefore be useful, along with paleoceanographic and paleoclimatic proxies, in providing this understanding. Indirect indicators of sea ice cover on the shelves can be found in the ice-rafted debris transported by sea ice, as well as biotic proxies. Other proxies need to be investigated.

In summary, the scientific issues are:

- The present and past processes on the arctic coasts and shelves that control ice formation (both sea ice and glaciers).
- The processes that can drive climate change in different parts of the Arctic over geologic time.
- The anthropogenic inputs over the last 50 years.
- The fluvial and oceanic fluxes to and across the coastal and shelf areas, and their impact on the arctic environment.
- The variability in sediment fluxes and processes affecting them in different parts of the Arctic.

The Tectonic History of the Arctic Basin

The opening of the Eurasian Basin was a major tectonic event that had profound effects on the world oceans because it allowed the fresh, ice-laden waters of the Arctic a pathway to the south. The exact effect of this opening on both the Arctic Ocean and the North Atlantic is still uncertain. The resulting Gakkel Ridge is different in its petrology, morphology, and structure from any other mid-ocean ridge. As such, it provides a superb test of the models and hypotheses developed from study of faster spreading ridges. Its uniqueness also makes it an excellent ridge to study the petrology of the upper mantle and the processes involved in upwelling, melting, and crustal generation. The similar curvilinear form of the Gakkel Ridge and the continental Lomonosov Ridge suggests that studying the internal structure of this rifted continental ridge and its relationship to the Gakkel Ridge may help our understanding of how continents rift. The Laptev Sea is also of great importance for studying the processes of initial continental rifting, for it is the southern terminus of the Gakkel Ridge and therefore

> The impact of global climatic change on social and economic systems in the Arctic should be evaluated, along with the impact of economic development in the Arctic on natural systems.

> **The opening of the Eurasian Basin was a major tectonic event that had profound effects on the world oceans.**

the site of structures resulting from the intersection of a spreading ridge and a continent.

The origin of the Amerasian Basin is problematic, and there are as many hypotheses on this subject as there are investigators (Lawver and Scotese 1990). In the earliest Mesozoic, the Arctic was either a low-lying, shallow marginal sea or dry land at much lower paleo-latitudes. Initial rifting occurred during or before the early Mesozoic in the Sverdrup Basin and along the continental margin from Banks Island to west of Point Barrow (Balkwill and Fox 1982; Grantz *et al.* 1990). By the mid-Cretaceous, the North Slope Chukotka block was rotated counterclockwise from the Canadian Archipelago by a relic spreading ridge currently buried in the Canada Basin (Taylor *et al.* 1981). The key to the origin of this basin lies in the nature and origin of the Alpha-Mendeleyev Ridge complex, the largest structural feature of the Arctic Ocean and comparable to the Alps in size (Weber and Sweeney 1990; Johnson *et al.* 1994). Another enigmatic feature is the Chukchi Borderland, which appears to be continental, with stratigraphic affinities to northwestern Canada (Grantz *et al.* 1998). Its tectonic history is key to understanding the Chukchi continental margin.

Ultimately, deep-sea drilling might provide the only resolution to these questions, but additional seismic and acoustical surveys, aeromagnetic and aerogravity surveys, and giant piston coring in locations where slumping has uncovered the underlying pre-Tertiary strata or crust would add tremendously to our understanding of basin evolution. Piston cores have already penetrated Eocene and Cretaceous strata on the Alpha Ridge (Clark *et al.* 1986; Clark 1988). These approaches can be undertaken immediately without the expense and problems of deep-sea drilling in the central Arctic Ocean.

Continental Shelf Resources

The widest shelves in the world occur in the Arctic. The potential resources on and under these shelves are equally vast, but remain largely unstudied, except for the Beaufort and Barents seas. The arctic shelves may contain the largest methane hydrate deposits in the world. These deposits are not only of economic interest: they also need to be identified and studied because of their potential importance both to global climate and to the generation of massive slumps (Haq 1998).

Basic data on the morphology, bottom sediment character, and stratigraphy of the shelves and slopes are unknown for most of these shelves, but are required to assess the mineral and hydrocarbon resources. Mapping the geomorphologic features is essential to understanding sedimentological processes that form canyons, gravity slides, and slope sediment and that determine the final fate of sediments and the mineral resources and contaminants that they transport. This mapping could best be done by submarines equipped with a Seafloor Characterization and Mapping Pod (SCAMP) and other acoustical bottom surveying equipment (Johnson and Brass 1998), or by surface vessels where ice conditions permit.

Onset and Long-term Variability of the Perennial Sea Ice

The initiation of a perennial sea ice cover in the Arctic should have had a major impact on global climate, according to models. Knowledge of the timing of this event and its relationship to global climate would be a major advance toward understanding the present interaction of the Arctic Ocean with global climate. Equally important is the understanding of how the ice cover has changed since its inception. Did it ever disappear only to reform? If so, which sediment proxies recorded this? Our ability to determine the past thickness and extent of the pack ice is limited, and much research on sediment proxies for these parameters is needed.

Paleo-proxies in the Arctic

The paleoceanographic record contained in arctic sediments may provide details of the past responses of the arctic system to changes in climatic variables. A prerequisite to interpreting this record is a baseline understanding of the contemporary elemental cycles within the Arctic and their mode of incorporation into the sedimentary record. At this stage, little is known of the distribution in the Arctic of tracers that are commonly used as proxies for environmental parameters, such as Cd/Ca as an indicator of phosphate levels (Boyle 1988). Only when the current spatial distributions of these tracers and their underlying biogeochemical cycles are better understood can variations in tracer abundance in the geologic record be used to constrain theories about the nature and strength of past biogeochemical processes and paleocirculation.

A particular concern in construction of paleosalinities in the Arctic is the recent assessment of errors in using $\Delta^{18}O$ residuals to calculate paleosalinities. Rohling and Bigg (1998) estimated that in regions where ice melt occurs, errors in $\Delta^{18}O$-based salinities would be about 1.9 ppt for 1 m of melt and as much as 4.4 ppt for 3 m of melt. This example emphasizes that an understanding of the proxies at lower latitudes doesn't necessarily translate directly to ice-covered regions.

Another major tool for arctic paleoceanography is the fossil content of the sediments. Although determining the timing is problematic, quaternary sediments record several dramatic fluctuations in the abundances of foraminifera and other biotic proxies, with the stratigraphic alternation of near-sterile and foraminifera-abundant intervals (Gard and Backman 1990; Ishman *et al.* 1996). We still understand so little about the arctic biota that we cannot be certain why this occurred, but it is probably linked to changes in Arctic Ocean circulation, pack-ice thickness, and snow cover. Understanding the relationships between arctic under-ice biota and these parameters would therefore greatly improve the interpretive value of biogenic proxies for arctic paleo-marine studies.

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4

Biogeochemical Cycles

Characterizing the Unique Arctic Marine Environment

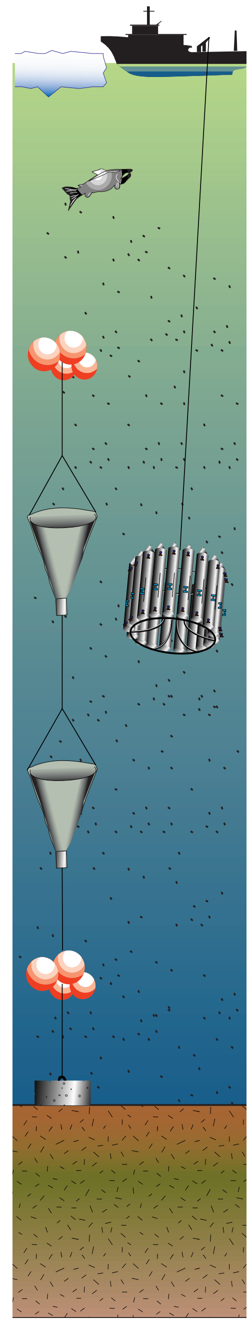
Understanding the Arctic Ocean's present and past roles in global biogeochemical cycles requires a well-developed knowledge of the fluxes of materials into and out of the Polar Basin as well as the types and rates of internal transformations that occur within the basin. Such information provides a background against which to assess the impacts of resource exploitation or climate change. It also provides the basis for interpreting sedimentary records of paleoarctic conditions.

The understanding of nearly every aspect of arctic marine chemistry is presently hindered by seasonally biased or nonexistent observations of fluxes and internal transformation rates. Specific requirements involve determining the magnitude and variability of riverine inputs, which deliver 10% of the global runoff to the Arctic Ocean; inputs from the Pacific through Bering Strait and from the Atlantic through Fram Strait and the Barents Sea; and outputs through Fram Strait and the Canadian Archipelago. In addition to the water-borne fluxes, atmospheric fluxes into the Arctic via precipitation, particulate deposition, and gas condensation, as well as outputs via gas evasion may be important for certain materials. Fluxes to and from the sediments and ice also need to be quantified.

Within the water column, rates of biologically and chemically driven transformation need to be ascertained. Significant progress can be expected if new technologies for remote and *in situ* sampling, such as chemical sensors and water sampling devices, are adapted or developed for year-round use under arctic conditions. Technologies specifically designed for arctic deployments may be required to address certain problems, such as determining the influence of ice-rafted materials on sub-ice biogeochemical dynamics. The availability of versatile year-round platforms, including moorings, autonomous underwater vehicles, aircraft-supported ice camps, and ice breakers to deploy such technological innovations in the Arctic is essential for advancing this research area.

The Role of Continental Shelves

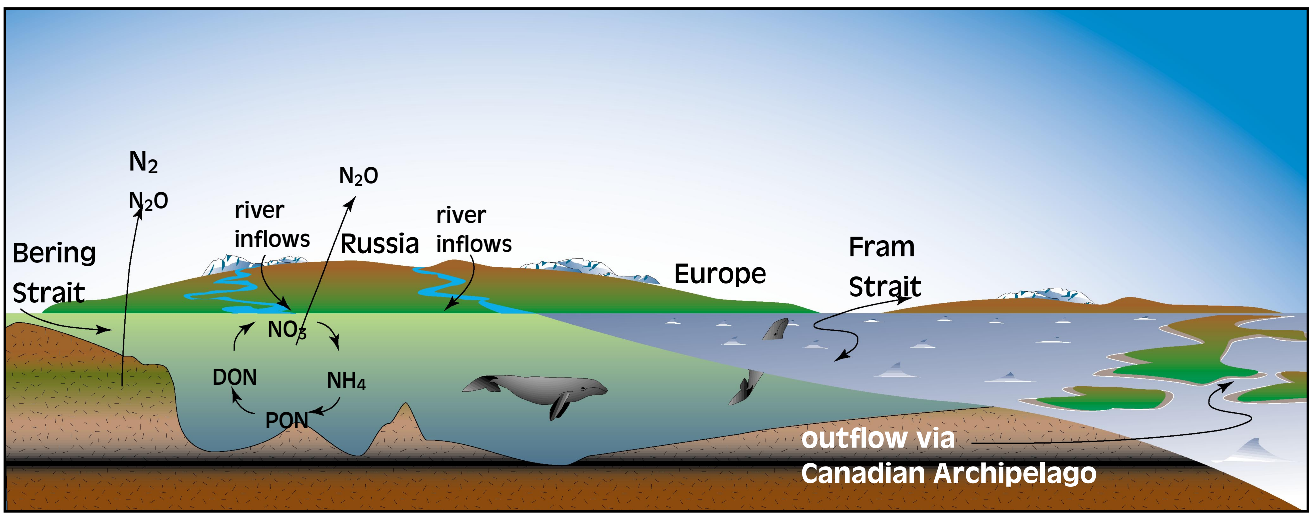
Since shelves constitute 30% of the area of the Arctic Ocean and can act as repositories for many materials over a range of time scales, the biogeochemical processes

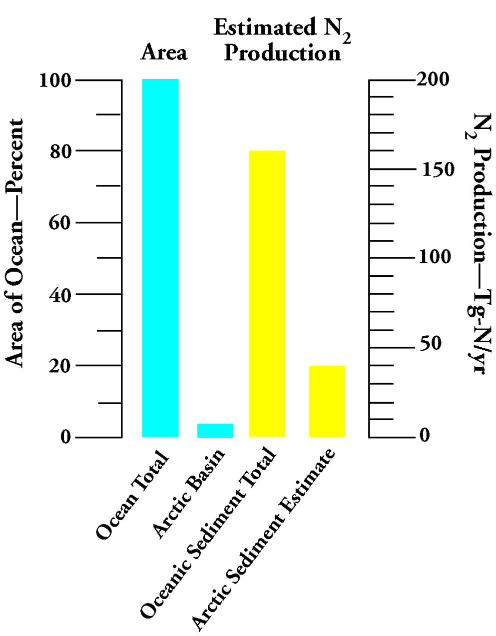


The understanding of nearly every aspect of arctic marine chemistry is hindered by seasonally biased or nonexistent observations of fluxes and internal transformation rates.

that occur on them have important consequences for attenuating and transforming the oceanic and terrestrial chemical signals. Shelf regions are subject to highly variable physical conditions, including fluctuating temperature and salinity regimes, changing current strength, and extremes in ice cover and light penetration. These factors make direct observations difficult but nevertheless essential for developing predictive capabilities.

It has been shown that denitrification can occur on the Bering, Beaufort, and Chukchi shelves at rates comparable to those for moderately productive shelf locations at lower latitudes (Devol *et al.* 1997). On the basis of its disproportionately large shelves (25% of the global ocean shelf area), the Arctic may serve as a sizable net sink in the global nitrogen budget (Christensen *et al.* 1987). It has also been proposed recently that the balance between nitrogen fixation and denitrification can significantly affect marine carbon sequestration on glacial to interglacial time scales (Falkowski 1997). Therefore, in order to understand global carbon dynamics, it is essential to know what role the Arctic

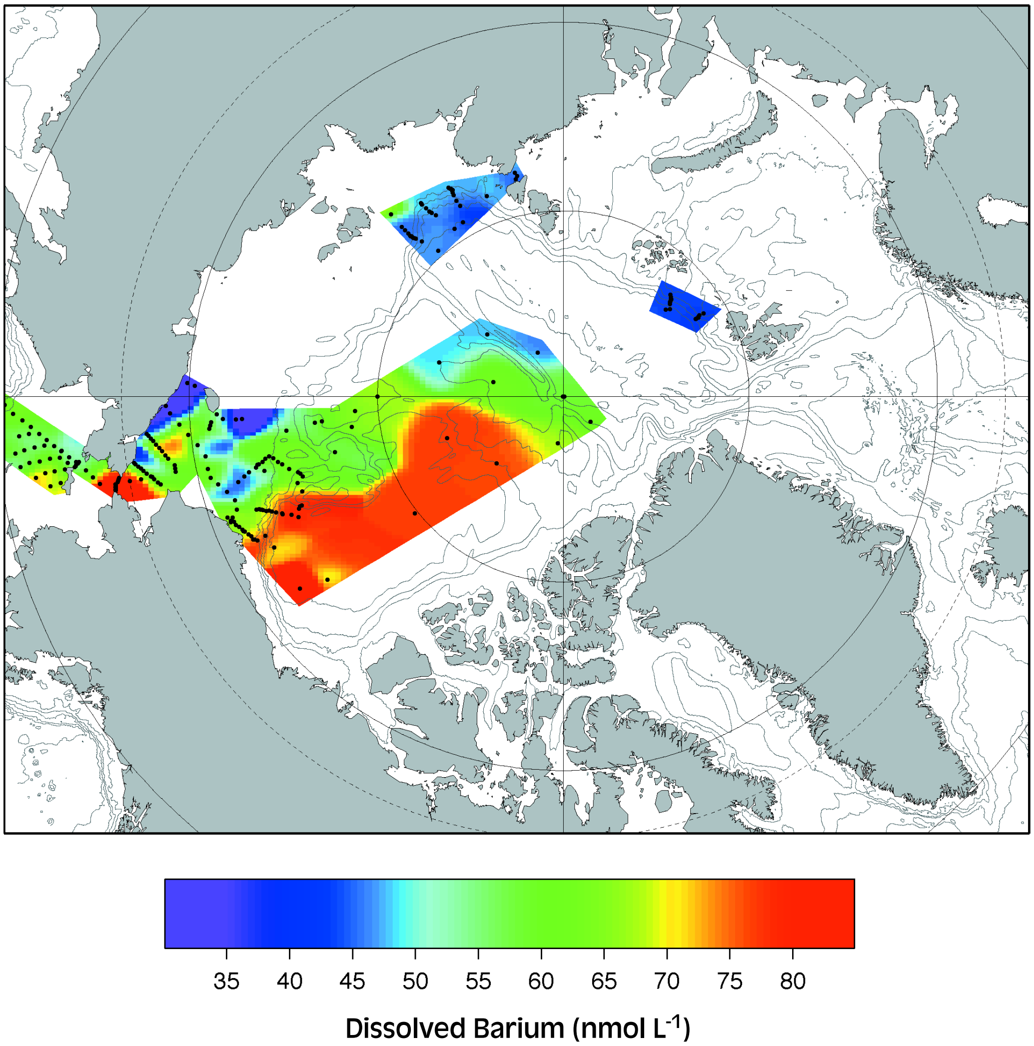




Various forms of biologically available or "fixed" inorganic (nitrate = NO_3^-; ammonium = NH_4^+; etc.) and organic (dissolved = DON; particulate = PON) nitrogen are contributed to the Arctic Ocean by Pacific waters entering through Bering Strait, by Atlantic waters entering through eastern Fram Strait and the Barents Sea, and by large river inflow. Nitrogen in these forms can be exported with outflows through western Fram Strait and the Canadian Archipelago. Within the Arctic, the productivity cycle converts nitrogen between these forms at rates that differ over the extensive continental shelves, in the central basin surface waters, and in the abyssal regions. Microbial processes can result in the production of gaseous nitrogen forms such as N_2 and N_2O, which ultimately escape to the atmosphere. This loss of "fixed" nitrogen, or "denitrification," occurs primarily in the sediments of the shelves and continental slopes of the Arctic. Denitrification in the Arctic Ocean may account for 25% of the global rate, which far exceeds the Arctic's areal importance (Devol et al. *1997). Figure drawn by Russell Mitchell.*

plays in the nitrogen balance of the world ocean. To quantify the arctic nitrogen cycle, a representative range of arctic shelf environments needs to be examined for denitrification rates, using carefully considered methodologies. Such studies should involve identifying forcing parameters to provide a context for understanding past changes and predicting future ones.

> **In order to understand global carbon dynamics, it is essential to know what role the Arctic plays in the nitrogen balance of the world ocean.**



Distribution of barium in the surface mixed layer of the Arctic Ocean in 1993. The Barnes objective analysis technique was used to generate this false-color contour image from data obtained during six oceanographic cruises to the Arctic in June–October 1993 (black dots show station locations). High barium concentrations observed over most of the Canada Basin reflect the influence of the Mackenzie River, while intermediate barium concentrations observed over the Mendeleyev Ridge and near the New Siberian Islands suggest the influence of discharge from Eurasian rivers. The area of extreme surface barium depletion in the vicinity of Wrangel Island and the Siberian coast likely resulted from a large plankton bloom occurring in conjunction with seasonal increases in solar radiation and melting ice. (See Guay and Falkner 1997). Application of barium as a tracer to distinguish North American and Russian river waters in the Arctic can be improved by determination of the magnitude and timing of barium's biogeochemical fluxes. Figure by Christopher Guay and Kelly Falkner.

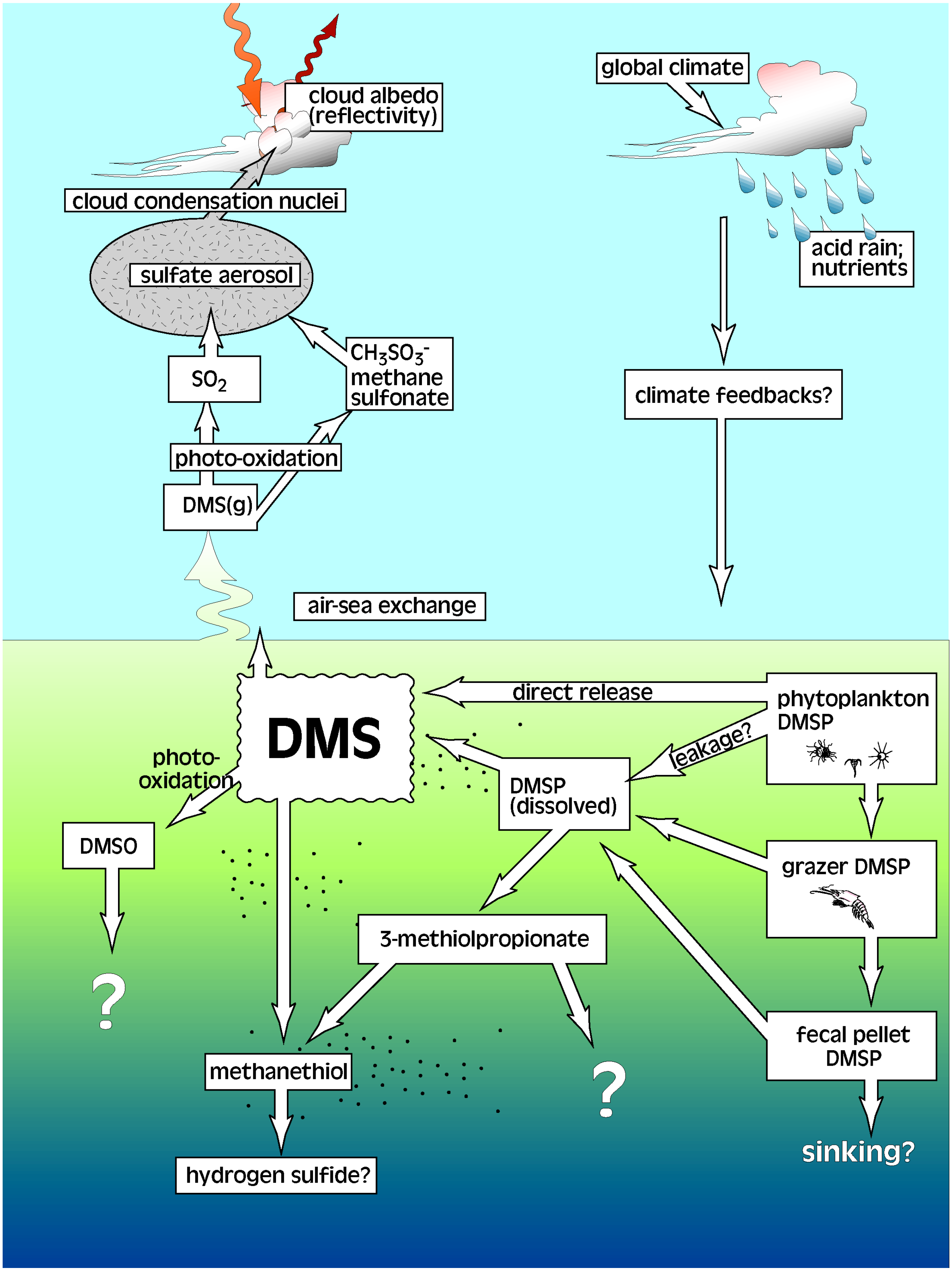
Significant progress can be expected if new technologies for remote and *in situ* sampling, such as chemical sensors and water sampling devices, are adapted or developed for year-round use under arctic conditions.

As is the case at lower latitudes, the cycles of nitrogen and phosphorus could be further decoupled in shelf environments due to strong associations between iron oxyhydroxide precipitates and phosphate. Under the reducing conditions that can occur near or at the sediment-water interface, iron can dissolve and release any adsorbed phosphate. The fate of desorbed phosphate depends upon transport and redox conditions. In the Arctic, resuspension processes associated with brine rejection and ice production may facilitate transport of both dissolved porewater and particulate phases. Direct observations of the rates at which sedimented particulate nutrients are returned to the overlying water column have been extremely limited due to logistic challenges. Multidisciplinary, process-oriented studies in shelf regions that cover a range of carbon export conditions are required to characterize the rate of geochemical transformations and the magnitude of carbon storage on the shelves. Organic and inorganic forms of materials need to be considered simultaneously. Clarifying these aspects of nutrient-related materials cycling is essential to properly exploit parameters such as NO, PO, N/P, silicate, and barium concentrations to track water masses, including the various contributions to the halocline (Aagaard *et al.* 1981; Jones and Anderson 1986; Salmon and McRoy 1994; Rudels *et al.* 1996; Guay and Falkner 1997; Jones *et al.* 1998).

Formation of sea ice in shelf regions leads to entrainment of resuspended sedimentary material within the ice. Natural and anthropogenic materials can also be deposited on the ice surface through atmospheric transport. The subsequent advection of this ice into the interior Arctic and its seasonal partial melting provide a unique mechanism for transporting a variety of chemical species, including the micronutrient iron (Measures in press), directly to the interior basin. Since this transport phenomenon is unique to the polar seas, it is important to determine what role it plays, and has played, in supporting the biogeochemical processes of the interior Polar Basin and in redistributing contaminants. It is also important to know the susceptibility of such a mechanism to climatic forcing.

Biogenic Gases

The Arctic Ocean remains an important unknown in global atmospheric chemistry. For example, the largest natural source of sulfur for the atmosphere is the emission of DMS from biological activity in surface seawater (see also Chapter 1). Once in the atmosphere, this sulfur gas is oxidized to sulfate aerosols within days. Among the highest DMSP (dimethylsulfonium propionate, which is a precursor to DMS) production for any marine organism has been shown to occur in ice algae (Levasseur *et al.* 1994) and in a common alga of polar waters, *Phaeocystis* (Matrai *et al.* 1995; Matrai and Vernet 1997). How much of this DMSP is released as DMS to become available for atmospheric exchange and subsequent conversion to sulfuric acid aerosol is unknown (Leck and Persson 1996). A similar situation holds for production of halogenated hydrocarbons such as methyl bromide and methyl iodide, greenhouse gases



Biogeochemical cycle of dimethyl sulfide (DMS) in the sea and its interaction with the climate system. Figure courtesy of Ron Kiene, developed by Russell Mitchell.

> To determine what controls the natural fluxes of the trace gases and their susceptibility to global change, it is essential to understand which signals come from anthropogenic trace gas sources and which from biogenic ones.

whose breakdown products consume ozone in the stratosphere (Moore and Webb 1996; Yvon-Lewis and Butler 1998). Production of bromoform by ice algae has been documented to be very high (Sturges *et al.* 1992), but again, release rates have not been characterized.

Remote sensing represents one possible avenue to quantifying the northern ocean's contribution to the atmosphere. Before remote sensing algorithms can be developed, however, direct measurements of ocean-to- atmosphere trace gas fluxes are needed, as well as an improved understanding of the parameters that govern their seawater concentrations. Very basic taxonomic and biochemical rate studies, in addition to larger scale atmospheric surveys, are required to assess present fluxes of biogenic radiatively active gases. To determine the processes controlling the natural fluxes of the trace gases and their susceptibility to global change, it is essential that signals from anthropogenic trace gas sources be distinguished from biogenic ones. For example, in the case of sulfur, fossil fuel burning also contributes sulfate aerosol to the Arctic. Techniques involving isotopic or compositional source characterization as well as a range of scales of air-mass trajectory analysis are probably needed to distinguish the sources.

Another greenhouse gas of importance in the Arctic is methane. Sizable reserves of methane in the form of ice-like methane hydrates, also known as clathrates, exist in onshore and offshore permafrost and underlying continental slope sediments in the Arctic. The global reserve of methane in hydrates is estimated to be twice as large as all other known sources of fossil fuels (Kvenvolden 1988; MacDonald 1990; Gornitz and Fung 1994). The development of methane hydrates as a fuel source is the subject of major new research in the U.S. and abroad, and arctic hydrates may be the first to be exploited for reasons of accessibility and existing infrastructure (Collett 1993).

In addition to these pending developments, a range of natural processes can destabilize hydrates, including tectonic uplift and warming by upward flow of deep fluids or by overlying seawater. The present offshore permafrost has been heated by the overlying seawater since the last sea-level rise, but it is unclear whether the methane that would be mobilized is oxidized in the sediments or seawater, or whether it makes its way to the atmosphere directly through the very shallow water column over the shelves (Kvenvolden 1993). Since methane is a potent greenhouse gas, release of destabilized clathrates has been implicated in global paleoclimate changes (MacDonald 1990; Nisbet 1990; Paull and Ussler 1991).

The magnitude of the Arctic's present contribution to the global methane picture must be determined in order to predict the impact of future arctic-derived methane. While insight can be expected from development-based programs, a range of basic research activities is required to understand the environmental implications of hydrates. For example, a first-order assessment of the present sediment-seawater and air-sea methane fluxes is essential. *In situ* detectors for methane in seawater are becoming commercially available and could be adapted for conducting widescale mapping and process-oriented observations via autonomous underwater vehicles, submarines, and surface vessels in the Arctic.

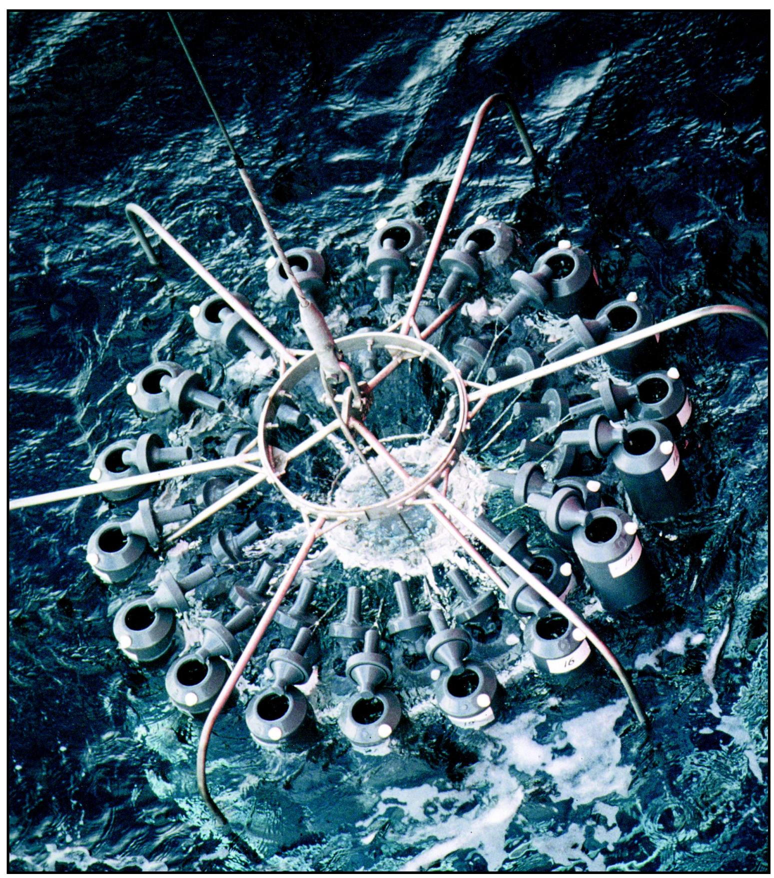
Understanding Contemporary Biogeochemical Cycles

Determining the magnitude of particulate fluxes from surface waters is critical to constraining a range of issues in the Arctic Ocean, including carbon cycling, the health of the ecosystem, the fate of contaminants, and interpretation of sediment records. To what degree the Arctic acts as a net sink for carbon and other materials will depend strongly on what fraction of primary production escapes remobilization in surface waters and sinks and on how much of this material is preserved in the sediments. Particle export, which is a sporadic process, is best assessed by combining methods such as time series sediment trap observations in a variety of locations with integrative approaches that involve interpretation of naturally occurring particle reactive radiotracers.

Logistic considerations appear to have limited the deployment of sediment traps in the Arctic Ocean. The reports that do exist suggest low particle export (2 to 3 mg/m^2/d) from permanently ice-covered regions (Hargrave *et al.* 1993), intermediate levels of export (12 to 27 mg/m^2/d) from areas of open water (Honjo 1990) or recurrent open water (Bauerfeind *et al.* 1997; Ramseier *et al.* 1997), and quite high fluxes (>300 mg/m^2/d) near ice edges (Hebbeln and Wefer 1991). Particle export estimates based on short-lived ^{234}Th were obtained in the Arctic Ocean during the 1994 Arctic Ocean Section (Moran *et al.* 1997). The largest export was reported for the Chukchi Shelf, while at some stations in the permanently ice-covered regions ^{234}Th appeared within analytical error to be in secular equilibrium, implying negligible export. Bacon *et al.* (1989), also using Th data, concluded that scavenging rates at the CESAR (Canadian Expedition to Survey the Alpha Ridge) ice camp were lower than in the most oligotrophic regions of other oceans.

While Moran *et al.* (1997) reported low, but non-zero, export from some permanently ice-covered regions, in other cases the export production implied by the ^{234}Th deficit was higher than the total production (Wheeler *et al.* 1997). Recent ^{232}Th data (Edmonds *et al.* 1998) indicate that advection and deposition of particulate material originating from the shelf (perhaps as ice-rafted sediments) may contribute to the

> Understanding sequestration of carbon and other materials in the Arctic requires estimates of the rate at which particulates are delivered to the deep waters; this information is also required to interpret the sediment record.



A 36-bottle rosette and CTD being lowered during the Canada-U.S. 1994 Arctic Ocean Section. Photo by James Swift.

Sediment traps should be deployed at key locations, and hydrographic and tracer sections should be carried out in the same areas.

scavenging signal in permanently ice-covered regions. It is important that these and other problems are resolved to reconcile apparent differences in particle export estimates and to settle questions related to contaminant fate and paleoclimate proxy calibrations.

Any comprehensive understanding of sequestration of carbon and other materials within the Arctic requires estimates of the rate at which particulate matter is delivered to the deep waters. This information is also required to interpret the sediment record. Although logistically challenging, long-term deployment of sediment traps and co-located cores should be accomplished at key locations in the major basins and on the continental shelves. Seasonal sampling for natural radionuclides and other related parameters in the water column should also be carried out along sections in the same areas.

5

Health of the Arctic Marine Ecosystem

Productivity, the Food Web, and Ecosystem Health

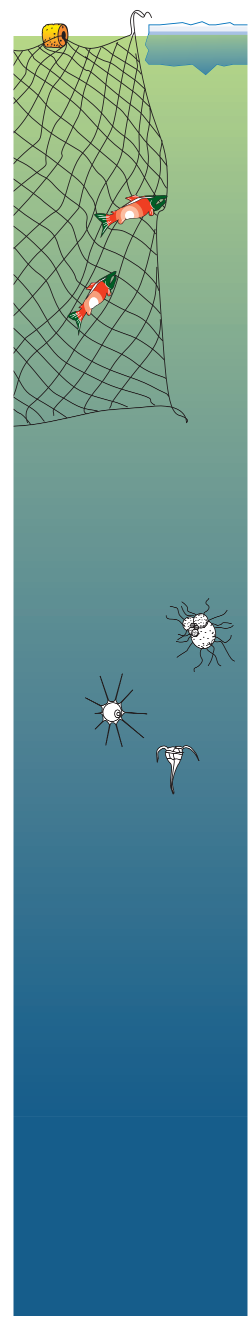
The long-held notion that the central Arctic Ocean is a biological desert due to light limitation by the ice and snow cover has changed dramatically in recent years. Substantial active carbon and nutrient cycling have been documented under the ice cover, which may provide a critical source of micro-nutrients, and certain shelf regions of the Arctic have recently been shown to support some of the highest primary and secondary production levels in the world ocean (Walsh *et al.* 1989; Springer *et al.* 1996).

Similarly, the notion of a pristine Arctic has changed, for the Arctic's remote location and relatively sparse population do not protect it from industrial and agricultural contaminants produced at lower latitudes. Chemical fingerprinting of ice, snow, seawater, and sediments has demonstrated delivery pathways that include the atmospheric as well as terrestrial and oceanic domains. Furthermore, the short lipid-rich arctic food chain renders the arctic ecosystem particularly prone to biomagnification of organic herbicides and pesticides and certain heavy metals that ultimately impact human inhabitants of the north.

A key issue for biological studies in the Arctic is the need to predict and understand marine ecosystem structure and function in the face of planetary change. There are also issues of general scientific interest embedded in the food chains of polar oceans, for example the regular large seasonal changes in plant growth driven by the annual insolation cycle. This characteristic affects the evolution of the life cycles of marine organisms and adaptations in their physiology. Studies on primary and secondary production are essential for understanding trophic level dynamics and food web structure, as well as biogeochemical cycling in the arctic ecosystem. The following sections outline important issues related to trophic level structure and function, contaminant input, and associated research tasks and strategies for significantly better understanding of the health of the arctic marine ecosystem.

Primary Production: Phytoplankton

Estimates of primary production and its fate in the arctic marginal seas, and especially in the central basins, are few



One of the fundamental issues for biological studies in the Arctic is the need to predict and understand marine ecosystem structure and function in the face of planetary change.

and severely limited by insufficient understanding of the controlling environmental factors. Until recently, production was considered extremely low, based on a sparse data set, but recent work by Cota *et al.* (1996), Wheeler *et al.* (1996), Gosselin *et al.* (1997) and Pomeroy (1997) indicate that annual primary production in the mostly ice-covered waters of the Arctic Ocean is about 15 to 30 gC/m^2. Primary producers in the Arctic include phytoplankton, ice algae, and benthic microalgae and macrophytes, which are generally assumed to respectively contribute about 95%, 5%, and <1% to panarctic marine productivity. Although ice algae have historically been considered of minor importance, recent studies indicate they may be more important to total primary production in the Arctic Ocean than previously estimated (Gosselin *et al.* 1997). Bottom ice communities (pennate diatoms) are most concentrated on first-year ice with higher light penetration and nutrient supplies. In summer when ice floes warm and diverge and melt ponds form, *Melosira* strands and infiltration communities (centric diatoms) may appear, but these are not ubiquitous (Cota *et al.* 1991; Horner *et al.* 1992).

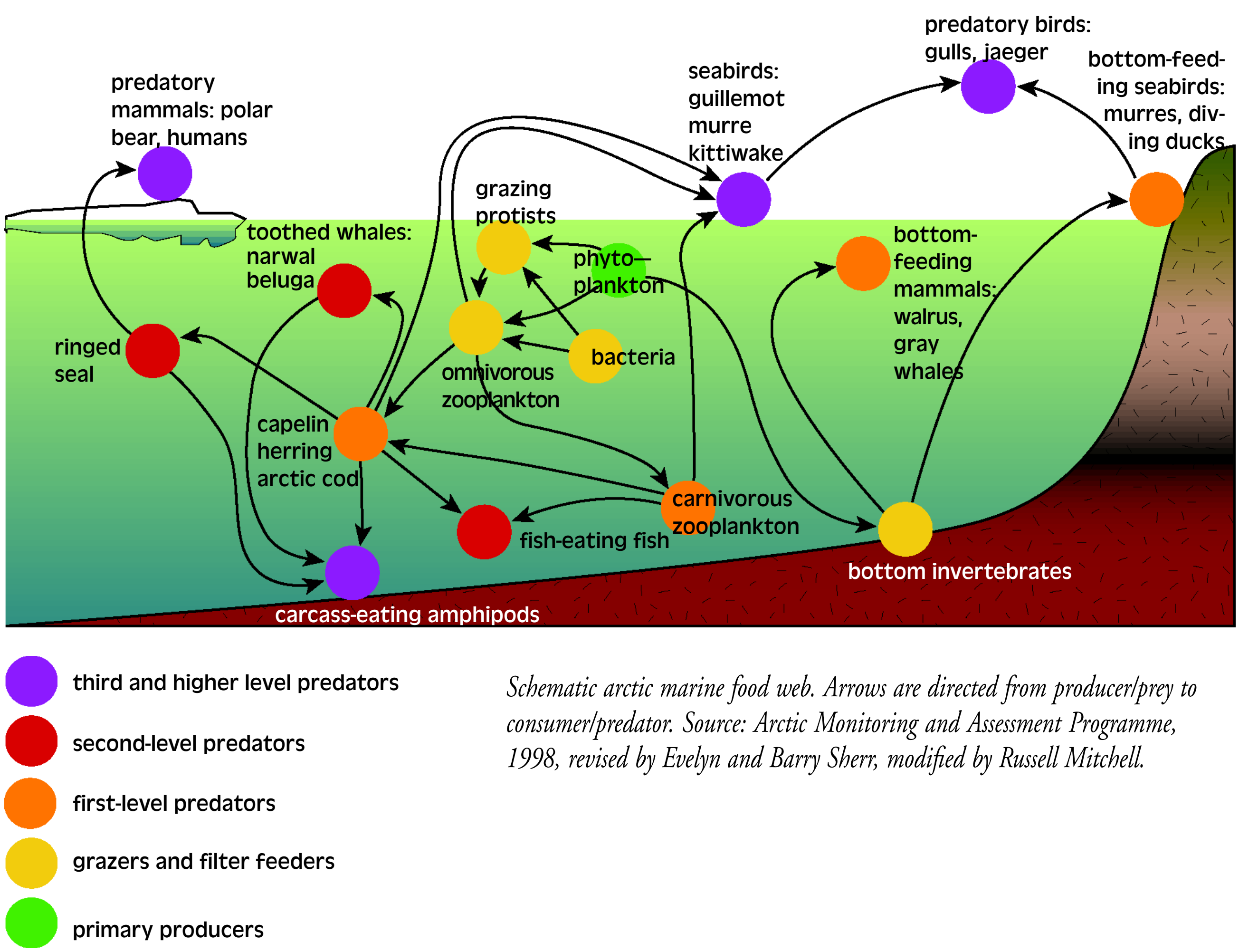
Sea ice and associated ice algae from the northern Bering Sea in spring. Photo by Lee Cooper.

By contrast, phytoplankton blooms are widespread in open waters and even in the perennial pack ice (Rey and Loeng 1985; Pomeroy 1997). The largest amount and variation in primary and secondary production occur over the continental shelves of the Arctic Ocean and surrounding marginal seas, which comprise an extensive area important to biological activity and carbon deposition or export. Annual production varies spatially from probably less than 50 gC/m^2 in parts of the Siberian shelf areas to perhaps as high as 800 gC/m^2 in parts of the Chukchi and Bering seas (Subba Rao and Platt 1984; Springer and McRoy 1993). Understanding the intensity, timing, and spatial extent of blooms and their dependence on specific environmental conditions (*e.g.,* light and nutrient supply) is critical for modeling arctic marine ecosystem structure.

The partitioning and cycling of organic matter into particulate, dissolved, and gaseous fractions is also important, and changes in ice cover will likely effectively change the significance of the Arctic as a source or sink of several gases of climatic importance (see also Chapter 4).

Secondary Production: Zooplankton and Bacteria

The pelagic food web in the Arctic Ocean may, like in most oligotrophic marine waters, vary from large phytoplankton that are consumed directly by microcrustaceans to a microbial food web. Recent investigations indicate that heterotrophic bacteria and protozoans in the microbial loop typically dominate late in the growth season (Cota *et al.* 1996; Wheeler *et al.* 1996). The primary link between plants and higher trophic organisms in the sea (*e.g.,* fish and some marine mammals) is zooplankton (Hansen *et al.* 1994; 1995), which often have adaptations allowing them to exploit periodically or episodically available food. These adaptations, along with the food supply, are usually tied to regional water mass movements or other potentially predictable physical aspects of the environment (Ashjian *et al.* 1997). Many zooplankton species can convert plant carbon into storage products (lipids) that fuel metabolism over the arctic winter. When plant carbon

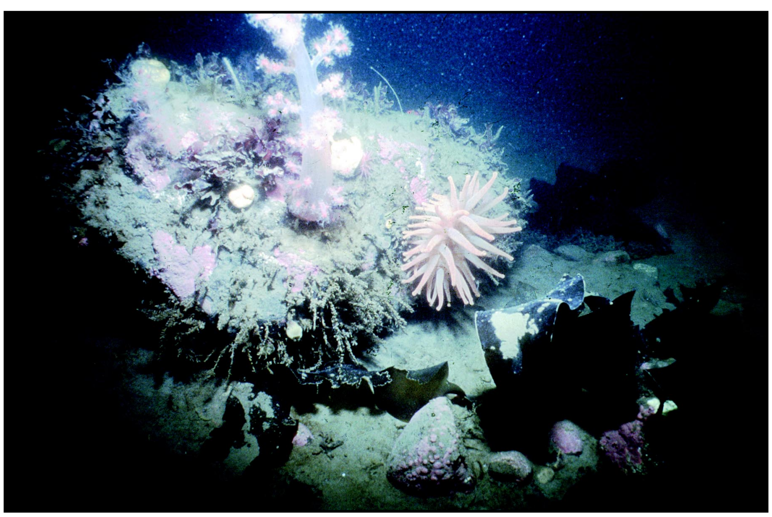


Schematic arctic marine food web. Arrows are directed from producer/prey to consumer/predator. Source: Arctic Monitoring and Assessment Programme, 1998, revised by Evelyn and Barry Sherr, modified by Russell Mitchell.

Estimates of primary production and its fate in the Arctic are few and severely limited by our not understanding the controlling environmental factors.

sinks uneaten to the seabed, however, it can be remineralized by bacteria and consumed by benthic organisms. Therefore, the interactions between bacterioplankton, zooplankton, and phytoplankton are important in lower trophic dynamic carbon cycling (Muller-Niklas and Herndl 1996).

Bacteria consume particulate and dissolved organic matter released by phytoplankton, and their role in structuring arctic marine communities requires further study. The relative roles of protozooplankton, microzooplankton (*e.g.,* copepods), and macrozooplankton (*e.g.,* jellies, big salps) in organic matter consumption also need to be assessed, particularly for their influence on phytoplankton standing stocks and ultimately on carbon transport out of the euphotic zone. Important topics include the role of zooplankton in structuring food webs by preferentially consuming protozoans (microbial loop), diatoms (classical loop), or ice algae, and the role of predation in population and community dynamics. Zooplankton grazers can drive a food web toward fish and bird production, while the absence of such grazers leads to a food web dominated by the benthos. An important question is whether this would change under reduced ice cover, causing a major shift in the relative importance of the benthic fauna and pelagic zooplankton, which in turn would have a dramatic cascading effect on higher-order food consumers.



Kelp and various fauna on a boulder on the nearshore shelf of the Beaufort Sea. Photo by John Olson.

Secondary Production: Benthos

Benthic fauna in polar regions are characterized by slow metabolic rates, long life spans, and large biomass (Dayton 1990; Grebmeier and Barry 1991). Short food chains are also characteristic, particularly on the continental shelves and in under-ice communities, emphasizing the tight connection and transfer potential of carbon and contaminants between lower and higher trophic levels (plants to marine mammals and humans). Benthic-feeding marine mammals (*e.g.,* walrus, gray whale, and bearded seals) are common in the Arctic, and they would be affected directly by a reduced ice cover. Factors affecting lower trophic dynamics have the potential to cascade quickly to higher trophic levels (fish, seabirds, marine mammals) and ultimately to humans.

Changes should also be expected in the efficiency of carbon transfer between primary producers (in the water column and the ice, as well as attached macrophytes) and benthic consumers. Reduction or loss of imported carbon from the euphotic zone would directly impact benthic production, likely resulting in disruptions of the migratory habits of endangered or locally or commercially important marine fish and mammals.

Benthic carbon cycling and community structure depend both on pelagic-benthic coupling of organic production and its deposition and recycling in the benthos (Dunton *et al.* 1989; Grebmeier and Barry 1991; Hobson *et al.* 1995; Wassmann *et al.* 1996). In turn, the transport of organic matter into, within, and out of the Arctic Ocean is largely dependent on *in situ* rates of primary production, pelagic food web structure, and a variety of physical conditions, including ice cover, currents, frontal systems, water depth, and stratification (Dunton *et al.* 1989; Grebmeier and Barry 1991; Wassmann and Slagstad 1993; Grebmeier *et al.* 1995; Yager *et al.* 1995; Slagstad and Wassmann 1997).

The Arctic contains 25% of the world's continental shelves and some of the largest populations of seabirds, fish, and marine mammals consumed by humans. Recent studies suggest that ice algae may act as an early season carbon source to initiate the biological production prior to significant phytodetritus flux (Ambrose and Renaud 1997; Rowe *et al.* 1997), although the influence of the ice algae probably depends on whether this production is over the shelf or the deep basin. Changes in carbon usage and transport over the continental shelves can also influence the amount of carbon exported into the Polar Basin, either to be used in surface waters or sequestered in deeper waters under the halocline of the Arctic Ocean. Most of the primary production in the deep basin is probably recycled in the surface waters, reducing carbon coupling to the benthos and thus limiting benthic production. The timing, extent, and type of primary production (ice algae vs. open water phytoplankton) can influence water column and benthic faunal communities, so that changes in these parameters may ultimately influence the relative importance of water column and benthic community dynamics.

Factors affecting lower trophic dynamics have the potential to cascade quickly to higher trophic levels (fish, birds, marine mammals) and ultimately to humans.

Secondary and Tertiary Production: Higher Trophic Levels

Higher trophic animals are key indicators of the health of the arctic marine ecosystem and have a direct impact on the indigenous populations of the north that consume them. Arctic marine mammals have undergone large population fluctuations due to human hunting and climatic fluctuations (Vibe 1967), and they are also influenced by such environmental factors as sea ice extent and prey availability. The consequences of ecosystem change in the Arctic to population diversity and density of marine mammals and birds (*e.g.,* in response to climatic warming) are of critical impor-

Brittle stars collected southwest of St. Lawrence Island, Bering Sea. Photo by Lee Cooper.

The Arctic contains 25% of the world's continental shelves and some of the largest populations of seabirds, fish, and marine mammals consumed by humans.

tance for the cultural survival of indigenous people.

Although bowhead and gray whales were hunted commercially throughout the Arctic and on their migration routes during the 19th century (Henderson 1984; Woodby and Botkin 1993), populations of both species have experienced a recognizable degree of recovery during the 20th century (Buckland *et al.* 1993; Zeh *et al.* 1993). Pacific walrus, a major benthic feeder in many of the shallow marginal arctic seas, is an important component of the ecosystem that is traditionally hunted by indigenous people (Krupnik 1980; Fay 1982). The walrus population depends on benthic prey and would probably decline if the summer and fall sea ice edge were displaced northward to areas where water depths exceed the animals' diving abilities (Fay and Burns 1988). Under those conditions, walruses would not have resting areas near their feeding grounds, and the energetic costs of foraging would significantly increase.

Numerous endemic and migratory species of marine mammals, seabirds, and fish are dependent on ice-edge systems and associated seasonal productivity (Ainley and DeMaster 1990). Changes in marine mammal seasonal distributions, geographic ranges, patterns of migration, nutritional status, reproductive success, and population dynamics will likely occur under arctic warming and changing ice extent (Stirling and DeRocher 1993; Tynan and DeMaster 1997). Ice-associated seals may be especially vulnerable to

Walrus females and their young in the Chukchi Sea. Females nurse their young on the ice and feed on benthic organisms below. Recent data indicate poor productivity and juvenile survival for the past three years or more. Reduced ice cover would require family groups to haul out on land, limiting access to many feeding areas. Photo by Brendan P. Kelly.

changes in ice extent (DeMaster and Davis 1995). Studies are therefore needed to understand potential linkages between lower trophic production and higher trophic prey utilization in variable ice conditions (pack ice, marginal ice-edge zones, polynyas, fronts, eddies, and open water).

Human Impacts

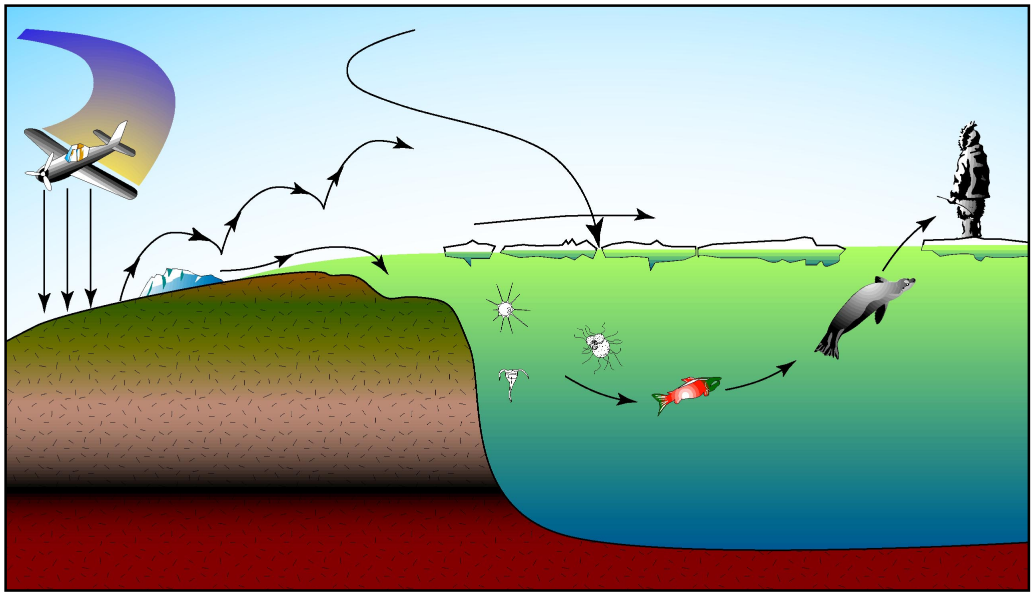
Continental shelves are sensitive to environmental forcing and can therefore provide an indication of more widespread changes in the global environment, even though the signal-to-noise ratios in the shelf ecosystems may be low. Shelf regions are also the focus of human marine activity in the Arctic, including the culturally based hunting activities of indigenous people, resource development, and shipping. Recent studies indicate increased levels of anthropogenic contaminants in the Arctic (persistent organics, heavy metals, and radionuclides), along with significant resource development impacts (*e.g.*, release of polycyclic aromatic hydrocarbons from oil production) (Macdonald and Bewers 1996; AMAP 1997; Jensen *et al.* 1997; Nilsson 1997; Strand 1997).

Organic Contaminants and Heavy Metals

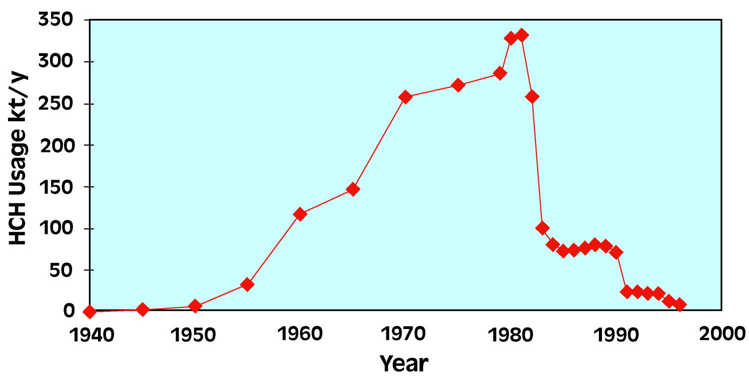
The short, lipid-rich arctic food chain enhances biomagnification of persistent organochlorine compounds (such as organic herbicides and pesticides) and certain heavy metals (lead, cadmium,

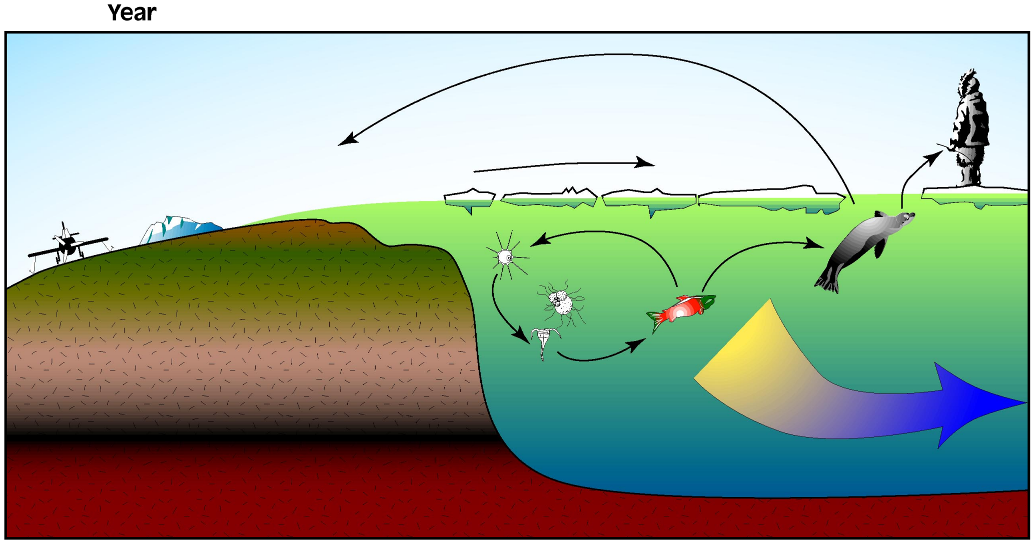
The short, lipid-rich Arctic food chain enhances biomagnification of persistent organochlorine compounds (such as organic herbicides and pesticides) and certain heavy metals.

Eskimo hunters butchering a bowhead whale. The whale was landed in September 1979 by Joseph Kaleak at Kaktovik, Alaska, and has been pulled up onto the beach. This whale was a male, 12.7 meters in length. A long-term research program initiated by the Alaska Eskimo Whaling Commission and conducted by the Alaska North Slope Borough Department of Wildlife Management continues to provide important scientific information on the bowhead whale (estimates of population size and trend, food habits, tissue contaminant levels, etc.). Photo by Tom Albert.



Since its introduction in the 1940s, hexachlorohexane (HCH: a common pesticide also known as lindane) usage increased rapidly but underwent dramatic declines during the early 1980s and 1990s (top), due mostly to reduced use by China and India. This decline was rapidly mirrored by reduced atmospheric concentrations in the Arctic. The Arctic Ocean has now changed from a sink to a source of HCH to the atmosphere (bottom). The upper ocean in the Canada Basin presently contains the world's highest concentration of HCH. Due to ice cover and stratification, efflux of HCH back into the atmosphere from the Arctic Ocean is relatively small (bottom), so that the major route for this historic HCH burden to escape the Arctic Ocean is via surface waters draining out through the Canadian Archipelago and Fram Strait. Figures from Kelly Falkner and Robie Macdonald, adapted by Russell Mitchell.





and mercury) that are transported from lower latitudes via marine and atmospheric pathways (Macdonald and Bewers 1996). Changes in trophic pathways and flux rates may therefore affect the bioamplification and delivery of pollutants to consumers of arctic fish, mammal, and bird populations, and may in turn jeopardize the health and economic future of northern populations. A better understanding of arctic ecosystem structure, including physical and biogeochemical interactions involved with shelf-basin exchange, would allow more realistic analyses of global change impacts on contaminant transport, transformation, and fate in the polar north.

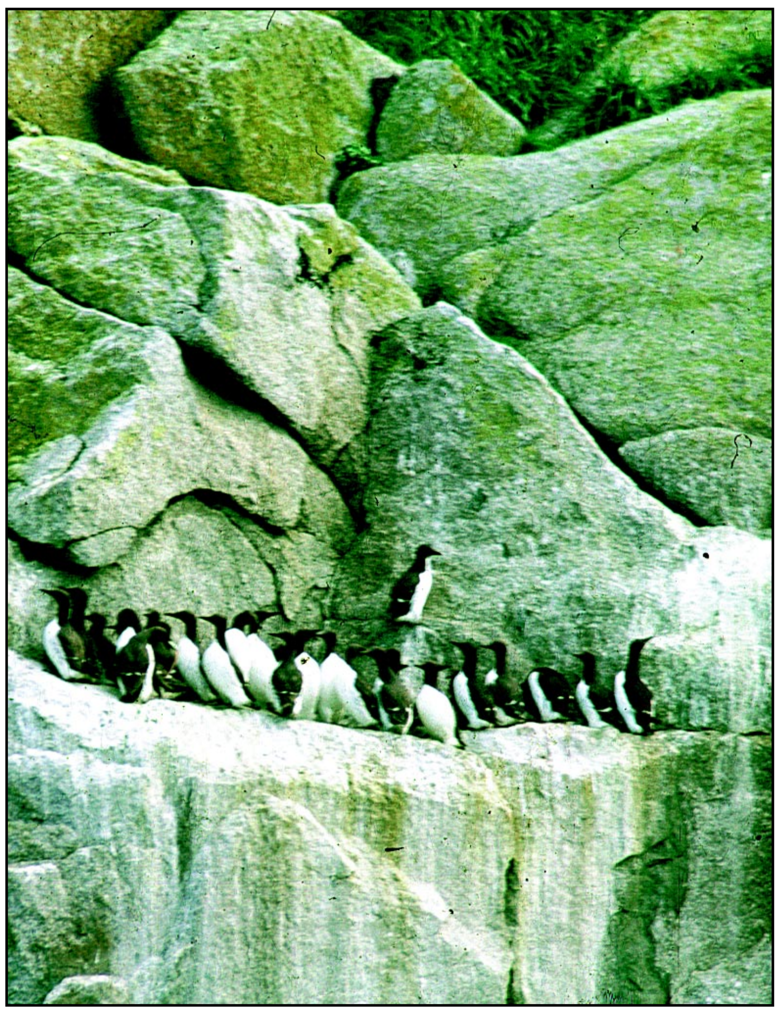
Radioisotopes

Concern about the fate of radioisotopes in the Arctic has provided the impetus for numerous physical and biogeochemical tracer studies over the past few decades. The early 1990s witnessed the release of classified information regarding the dumping of nuclear wastes by the former Soviet Union into the marginal seas and the watersheds of the Russian rivers emptying into the Arctic Ocean. Recent studies undertaken as part of the U.S. Office of Naval Research Arctic Nuclear Waste Assessment Program (Layton *et al.* 1997) and the international Arctic Monitoring and Assessment Programme (AMAP 1997) have evaluated anthropogenic radioisotope inputs to the arctic system, including risk assessment analysis of biological components of the ecosystem. While overall these data indicate minimal health risk from radioisotope contamination of the arctic marine environment, radionuclides appear more mobile than had been assumed previously, and catastrophic releases remain a possibility, so that continued scientific vigilance is important (Macdonald and Bewers 1996; Layton *et al.* 1997).

Effects of Ozone Depletion

Ozone depletion events have occurred in the Arctic over the past decade or two. Anomalies such as the 1996 ozone hole have developed over small areas of the Arctic, typically lasting several days. In addition to short-lived ozone depletion events, a general downward trend of arctic ozone concentrations has been

> **Higher trophic animals are key indicators of the health of the arctic marine ecosystem, and have a direct impact on the indigenous people of the North who consume them.**



Murres on a cliff in the Bering Sea. Photo by Jacqueline Grebmeier.

> Understanding the proximate and ultimate controlling factors of various trophic level standing stocks and production rates is essential for interpreting ecosystem changes.

detected. Average concentrations of arctic ozone were 10% lower in the 1990s than in the 1970s (AMAP 1997). Associated with the ozone decrease has been an increase in UV radiation reaching the surface. Environmental effects of UV on photosynthetic carbon fixation in marine autotrophs, and ultimately on man, is of growing concern in polar regions. Marine organisms are sensitive to UV, and ozone depletion is known to have significant effects on phytoplankton productivity in the Antarctic, resulting in a reduction in the global sink for anthropogenic carbon. Further disruptions of marine food webs may occur because UV radiation can damage zooplankton and fish (particularly the egg stage in shallow waters), which would ultimately impact higher trophic levels, including humans.

Research Needs and Strategies

Research issues important to understanding arctic ecosystem dynamics require knowledge of seasonal and interannual variations in ice cover and other physical parameters influenced by climate variation. Understanding the proximate and ultimate controlling factors of various trophic level standing stocks and production rates is essential for interpreting ecosystem change occurring presently in the Arctic, as well as interpreting past shifts in trophic level importance, including paleoentologic proxies from the sediment record. Major research issues include:

- The distribution, magnitude, and seasonal variability of primary production (total and new) and secondary production (bacteria, zooplankton, and benthic fauna).
- The biogeochemical cycling of organic sulfur and halogenated compounds among the various food-chain compartments (phytoplankton, grazers, bacteria).
- The causes and consequences of variations in abundance (space and time distributions) of higher trophic organisms (fish, seabirds, marine mammals).
- The quantity of fixed carbon consumed, sequestered, and exported within each ecosystem (shelf, slope, basin).
- The effects of human impacts on the Arctic marine ecosystem (individual species to ecosystem level), including increased UV radiation and organic contaminant cycling.

It is clear that appropriate research strategies are needed in order to describe and understand the arctic marine ecosystem, including a mixture of retrospective analyses, acquisition of time series, process studies, and modeling. Evidence of change in the arctic environment is accumulating rapidly (see also Chapter 2), and although the effects of these changes on physical and chemical dynamics are now being recognized, coincident effects on the biological systems are more difficult to assess. Nevertheless, understanding ecosystem response to perturbations, be they natural oscillations, global warming, or anthropogenic contaminants, is critical to evaluating the past, present, and future of the Arctic. Ultimately, ecosystem modeling must be used in conjunction with field analyses to predict the effects of global changes on biological production and the fate of organic carbon in the Arctic.

More information on the rates and controls of primary production (both phytoplankton and ice algae) in the marginal seas and the central Arctic is urgently needed to assess and predict the effect of environmental changes on arctic ecosystems and biogeochemical cycles. Present estimates of arctic primary production suffer from chronic spatial and temporal under-sampling, as well as reduced efficacy of satellite data because of ice, snow, and cloud cover. Very few time series exist to establish seasonal patterns of production, and there are almost no observations during breakup, which may be a time of high primary and secondary production.

Both system-based and process-oriented studies are necessary for assessment of biological production in the arctic marginal seas and the central Arctic. System-based studies investigate geographic, spatial, and temporal variations of key biological and environmental parameters. Process-oriented studies are necessary to determine the relationships between variations in environmental and biological parameters and the production and fate of fixed carbon throughout the ecosystem.

A useful approach to understanding the arctic marine ecosystem may be through intensive study of subsets that can be scaled up to regional and larger assemblies via coupled modeling. For example, the significance of the shelves to the larger arctic marine ecosystem is currently being addressed through the NSF Western Arctic Shelf-Basin Interactions (SBI) project (Grebmeier *et al.* 1998). This effort is intended to illuminate the physical and biological shelf and slope processes that influence the structure and functioning of the arctic marine ecosystem, with the larger goal of being able to predict the impact of global change on ecosystem function. Other regional studies have been developed to understand the role of polynyas in the arctic ecosystem (Grebmeier and Cooper 1995; Yager *et al.* 1995).

In addition, there is a new focus on understanding the development of ridge systems and hydrothermal vent communities in the Arctic. The NSF and NASA are also planning the use of the Arctic as a regional laboratory for studies in astrobiology, with the ice-covered Arctic Ocean considered an analog of possible habitats for microbial life on other planetary bodies, such as Jupiter's ice-covered moon Europa (AMES report 1998).

6

Strategic Considerations

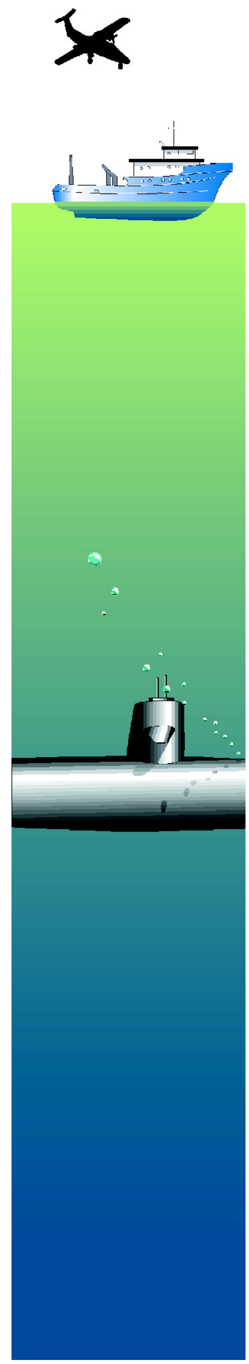
The practical constraints on arctic marine research are considerable, ranging from those imposed by a difficult working environment, through requirements for international arrangements in politically sensitive areas, to a need for significantly increasing our national capabilities. Given these constraints, we believe that an effective strategy must:

- View the Arctic in a global context.
- Move toward a symbiosis of measurement, modeling, and retrospective analysis.
- Provide access to the entire marine Arctic.
- Lead to effective international coordination.
- Develop and maintain efforts sufficient to create usefully long time series.
- Extract and use existing data in both the public and private sector.
- Recognize the dependence of arctic coastal residents on the marine environment.
- Consider existing and proposed industrial activities in the marine Arctic.
- Promote interagency cooperation.

We recognize that while the marine Arctic is seriously under-observed and its modeling is deficient in major aspects, enough progress has been made during the past decade to believe that a useful predictive capability can realistically be achieved. Doing so, however, will require a considerable expansion of our present capabilities.

Scientific Access

Scientific access to essentially the entire Arctic Ocean and its peripheral seas is required during the next decade, for there are substantial limits to what can be achieved through piecemeal investigations. This will require stably funded and scientifically responsive logistics, but it will also require predictable scientific access to the exclusive economic zones that cover much of the Arctic. In particular, it will require mechanisms that can with some confidence provide access to the Russian shelf and slope regimes, since these are vital components of the arctic system. This in turn will require commitments at levels of government far higher than is customary in arranging such work. It is also important that the large Canadian marine Arctic, including the passages through the Canadian Archipelago, remain scientifically accessible in the face of changing regional governmental structures and responsibilities in Canada.



> We need predictable scientific access to the entire Arctic Ocean and its peripheral seas.

The importance of the arctic shelves and slopes looms very large in the research strategy of the next decade, and one cannot hope to fully meet the strategic goal of predictive capability without an understanding of all the major shelf areas. We note that scientific programs, including those involving deep drilling, have been successfully completed on other continental shelves around the world, and these programs may therefore provide a guide for the arctic shelves. We note further that the national interests are addressed by such work because of the likely importance of the arctic shelves to national and global economies of the future, and because of the importance of understanding global environmental linkages.

A sustained effort should also be made to involve the petroleum companies in collaborative research and to induce them to share the wealth of geologic and oceanographic data that have been gathered in such shelf areas as the Beaufort Sea. Indigenous people also have a vast knowledge of and interest in the coastal marine environment that might be tapped through their involvement in basic and applied research.

New Methodologies

There is a clear need to develop new methodologies that are workable in ice-covered waters. Much of the instrumentation and technique that has come to the fore in open ocean research in recent years, or is contemplated, is presently difficult or impossible to apply to the Arctic. This includes methodologies as diverse as Lagrangian profilers, sea-surface altimetry from satellites, and expendable moorings that require surfacing to transmit their data.

For certain parameters, such as velocity, temperature, salinity, and ice thickness, moored measurements are presently possible anywhere within the Arctic Ocean, given the necessary logistical support, but such measurements are expensive, and new technologies, including acoustic ones, should be systematically explored. Other parameters, including a variety of tracers, are also important constituents in such a long-term measurement strategy.

We therefore recommend that a long-term dedicated effort be instituted to develop measurement techniques that with confidence can be applied to ice-covered seas. There may be special opportunities for forging new partnerships in this undertaking, both internationally and with other government agencies and industry, for example in developing and using autonomous underwater vehicles.

Sustained Measurements

There is a further distinct need for sustaining key measurements over a long period of time (on the order of several decades). For example, a coordinated set of biologically relevent time series measurements in the most important physiographic regions in the Arctic would significantly advance the ability to evaluate ecosystem evolution in a changing Arctic. Guidance on the low-frequency variability of the system is also obtainable both from studies of the paleorecord and from simulations and theory, but this does not obviate the need for direct measurements. Such long-term monitoring does not easily fit within the NSF/academic system, except perhaps for Environmental Observatory sites, which suggests that cooperation from other agencies must be sought, whether domestic or foreign. Highly successful examples of such international and interagency cooperation in the Arctic are the International Arctic Buoy Programme, as well as numerous polar-orbiting satellites with special capabilities for the remote sensing of ice and other parameters of interest. For example, the multi-year, satellite-derived geophysical data sets now available provide a rich store of information highly relevant to the principal research themes of this report. Important long-term international environmental monitoring programs, such as the Global Ocean Observing System (GOOS), and international marine paleoclimate investigations such as the Ocean Drilling Program have traditionally avoided the high latitudes, but a deliberate engagement of arctic marine research with these efforts should be sought.

In general in the Arctic, one has relatively little understanding of the scales of variability, whether spatial or temporal, but dynamical considerations suggest that at least the spatial scales are smaller than at mid-latitudes. This then places a special burden both on observational strategies and on numerical simulation, and resolving these issues of scale and their importance will require a more focused research effort.

The Need for Cooperation

We believe that NSF alone cannot support the full range and depth of research required for carrying out the strategic goal of acquiring a predictive capability for the marine arctic and its links with the global atmosphere-ocean system. Rather, an effective means of coordinated planning, support, and conduct of research on a multiagency basis must be sought, as well as better links with the private sector. Pollutant research and atmospheric sciences are examples of fields currently suffering from deficient interagency cooperation. Similarly, in recognition of the Pan-Arctic nature of such marine research, an effective means of international cooperation is required. This may take a variety of forms, including joint funding, bilateral agreements, sharing research infrastructure, and close logistical coordination. Within the international research community, Canada provides a natural partner with whom to initially develop such systematic and sustained cooperation, as amply demonstrated by the successes of the 1994 Canada-U.S. Arctic Ocean Section and the recently concluded field phase of the Surface Heat Budget of the Arctic Ocean study (SHEBA). The experience gained can then be used to develop similar arrangements with other nations, especially Russia. Existing international programs such as the Arctic Climate System Study of the World Climate Research Programme and the Ocean Drilling Program can contribute additional experience and networking potential.

"Effective means of coordinated planning, support and conduct of research on a multiagency basis, and of international cooperation, are required."

The U.S. Coast Guard cutter Polar Sea *and the Canadian Coast Guard ship* Louis S. St. Laurent *exiting the ice after their historic scientific crossing of the Arctic Ocean from the Pacific to the Atlantic. Photo by Knut Aagaard.*

> Shore support stations are essential for marine science in the nearshore zone, and for work requiring field camps and aircraft support.

Cooperative arrangements of this nature share with large coordinated science projects the ability to effectively leverage and use resources, including logistics, and to promote multidisciplinary approaches, but they need to be considered within the context of an overall balance that also encourages fresh insights and innovative approaches. The NSF has a special role to play in this regard, safeguarding and promoting opportunities to test new ideas and approaches. As interagency and international arrangements prove workable, we foresee NSF taking on a relatively greater role in promoting science outside such structured and coordinated scientific programs.

Resources and Logistics

Just as new ways of working are required to achieve these goals for an effective scientific presence in the Arctic in support of national needs, substantial new resources are also required. Predictable availability and known paths to these resources are important elements in their effective use. Furthermore, the individual investigator should be encouraged to form partnerships whenever practical to best utilize resources. Means should also be found to share financial resources, facilities, and logistics internationally. The participation of NSF in the international Ocean Drilling Program may provide a useful model for using international scientific infrastructure to achieve long-term and complex goals, such as drilling in the Arctic Ocean.

The complex and expensive logistics of arctic field work suggest that coordination of logistical support is important and most easily accomplished with large, well-planned initiatives. For example, deep-sea drilling in the Arctic Ocean will be required to resolve many of the important questions about the geologic structure and evolution of the Arctic, but such drilling needs to be preceded by giant piston coring and acoustical surveys, the execution of which should be aggressively pursued now.

Arctic marine research in the U.S. has been severely limited by the absence of a surface vessel capable of carrying into the ice on a regular basis the complex array of scientific facilities that is an essential part of modern marine science. The advent of the USCGC *Healy* into the U.S. research fleet creates the opportunity for the U.S. for the first time to support its science community with a dedicated and suitable platform available throughout the year. It also provides the opportunity for the U.S. to become a full international partner with other nations who have earlier made such an investment. To convert these opportunities to working realities will require that an administrative and operational practice and culture be developed that is capable of bridging the gap between the military operator (the Coast Guard) and the largely civilian users. This development will require support at the highest level within the cognizant organizations and a sustained and creative effort by knowledgable working groups with clear mandates.

To make the *Healy* a working reality in support of science will also require stable funding that does not place the working scientist in the untenable position of having to secure operational funds. We further believe that the scientifically most effective funding mechanism is one that provides support for the scientists themselves on a competitive basis and that may be funded by a variety of agencies and sources, including foreign. Finally, effective use of the *Healy* will require a long-term planning process to assess regional, seasonal, and programmatic emphases on a multi-year basis, and to identify and coordinate schedules with escort or companion vessels on deep penetrations of the Arctic Ocean. This may not comfortably fit the short proposal cycle of NSF and other agencies, and it may therefore require ingenuity in adapting agency practice to the realities of arctic planning.

We consider it unlikely that the *Healy* will be able to meet all the science requirements for work in or near ice-covered waters, in part because of the anticipated priority use of the vessel in areas more difficult to reach, and in part because the vessel will be expected to cover the entire Arctic. We therefore foresee the need for an ice-strengthened research vessel of medium size to work in the marginal ice zone of the Western Arctic in summer and fall and in the Bering Sea throughout the winter. This issue is best addressed by a dedicated panel, building on present and past deliberations.

The use of submarines as scientific platforms in the Arctic dates back to the 1930s, but only recently, through the SCICEX program, has a sustained and broadly based experiment in such use been performed. The five dedicated SCICEX submarine cruises have provided an unprecedented opportunity to observe the ice cover, upper ocean, and sea floor; and an evaluation of that program is currently under way in the form of a SCICEX 2000 workshop report. Published results to date (*e.g.,* Guay and Falkner 1997; Morison *et al.* 1998; Steele and Boyd 1998; Smith *et al.* submitted) point to the considerable scientific potential of submarines, especially in a survey mode, where submarines can truly excel. For certain other applications, such as benthic sampling, the limitations appear severe. This suggests that the maximum scientific return will be had when programs carried on submarines and other platforms, such as ice breakers, are carefully coordinated both scientifically and operationally. We also strongly encourage the continued release of both past and future submarine data, which provide the only large-scale measurements of ice thickness in the Arctic.

The principal shore facility in the U.S. for arctic marine science has been the former Naval Arctic Research Laboratory at Barrow, now owned by the Ukpeagvik Inupiat Corporation and used in support of both education and research. For marine science in the nearshore zone and for work requiring field camps and aircraft support, shore support stations are essential. It is likely that aircraft operating from such shore bases will prove a mainstay of future work on the continental shelves during winter. We further believe that providing satisfactory shore support will

Making the Healy a working reality in support of science requires bridging the gap between the military operator and the largely civilian users.

Artist's rendition of the USCGC Healy, *now under construction.*

Multinational agreements for scientific studies need to be raised as critical issues in effective political fora.

require international investments in infrastructure at a circumpolar series of sites, perhaps six to eight sites altogether. In addition to the laboratory at Barrow, diverse models for such stations range from the Canadian bases in Tuktuyaktuk and Resolute Bay to the NSF facilities in the Antarctic and New Zealand, although with respect to the latter model the Arctic presents special problems, primarily associated with political and administrative boundaries.

International Coordination

Given that patterns of arctic climate change, for example, are nonuniform (Parkinson 1992; Chapman and Walsh 1993; Martin *et al.* 1997), it is important to integrate U.S. programs with other national and international ocean science programs to obtain a Pan-Arctic perspective. For example, the Arctic is a very large ecosystem indeed, and full understanding of the levels and controlling factors for biological production will require coordinated international efforts to attain enough spatial and temporal coverage. Parallel research programs in the marginal seas and basins of the eastern and western Arctic will therefore be necessary to assess biological production in the Pan-Arctic system.

The UIC-NARL Facility (formerly the Naval Arctic Research Laboratory) now operated as a multi-use facility by its owner, the Barrow, Alaska, based Ukpeagvik Inupiat Corporation. The facility now houses academic, research, and logisitics programs. Photo by Tom Albert.

International coordination with Canada, Russia, Germany, Sweden, Norway, and Denmark/Greenland is both essential and efficient. For example, Canada has excellent shore-based logistic capabilities in the Arctic, and arrangements for regular use by U.S. investigators should be initiated. We note also that it was international efforts that succeeded in carrying out scientific traverses of the deep arctic basins by ice breakers, and that are currently promoting broad initiatives in climate (the Arctic Climate System Study of the World Climate Research Programme) and solid earth sciences (the Nansen Arctic Drilling Program). Furthermore, if one is to understand how the Arctic is or is not changing, long-term studies are essential, and these studies will require international cooperation.

International collaboration is particularly essential for working over the arctic continental shelves. Multinational agreements for scientific studies need to be raised as critical issues in effective political fora. Leaving requests for access to foreign waters up to the principal investigator is not adequate for collaborative work, particularly within the Russian exclusive economic zone. It would likely also prove valuable to establish a U.S. government liaison in collaborating countries to support arctic research and operations.

Finally, to encourage international collaboration, funds should be provided for invited workshops and symposia and for the participation of foreign scientists in fieldwork and collaborative planning efforts with NSF-funded scientists.

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