Oceanus®

Volume 29 Number 1, Spring 1986

THE ARCTIC OCEAN

Oceanus®

ISSN 0029-8182

The International Magazine of Marine Science and Policy

Volume 29, Number 1, Spring 1986

Published by Woods Hole Oceanographic Institution

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Editorial correspondence: *Oceanus* magazine, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Telephone (617) 548-1400, ext. 2386.

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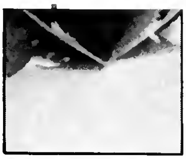

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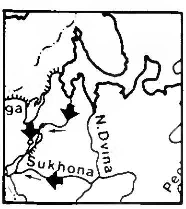

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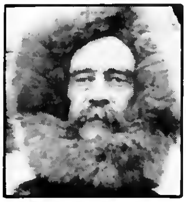

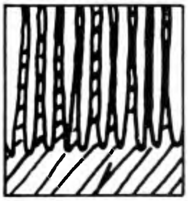

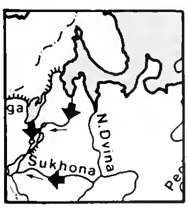

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U.S. explorer Robert E. Peary, considered the discoverer of the North Pole. After several expeditions in Greenland and the Arctic, Peary reached the Pole in April 1909. His claim of discovery was challenged by fellow American Frederick Cook, who reported reaching the Pole the previous April. (Photo courtesy of Springer/Bettmann Film Archive)

Introduction

by James H. Zumberge

The Arctic Ocean has tantalized explorers, beckoned scientists, and lured adventurers for centuries. The major attraction of the Arctic Basin a hundred years ago was that it contained the North Pole of the planet Earth. In the late 19th and early 20th centuries, men struggled to be the first humans to set foot on the unique geographic point. Since 1909, when Robert E. Peary and Matthew Henson reached that goal by dogsled, others have achieved it by almost every means conceivable. Richard E. Byrd and Floyd Bennett flew over the Pole in an airplane in 1926, and Umberto Nobile and Roald Amundson flew across the Pole in the dirigible, *Norge*, in the same year.

In 1937, the Russians, under the leadership of Otto Schmidt and Ivan Papanin, landed at the Pole in an airplane, and, in 1958, the *U.S.S. Nautilus*, a nuclear submarine, conquered the Pole on a cruise beneath the ice. The Soviet nuclear-powered icebreaker, the *Arktika*, now the *Leonid Brezhnev*, was the first surface ship to reach the Pole, a feat accomplished in August, 1977.

Today, a travel agency in Seattle, Washington, can arrange for anyone who can pay the price to be landed at the North Pole in a Twin Otter aircraft!

The Arctic in general and the Arctic Ocean in particular have remained areas of considerable scientific interest since the first International Polar Year—1883—when the scientific world first singled out the polar regions as areas of international scientific value.

Scientists and explorers from all countries bordering on the Arctic Ocean have advanced the knowledge and understanding of this perennially ice-covered sea and its bordering lands during the 19th and 20th centuries. However, the impetus has changed somewhat from the mere satisfying of scientific curiosity to the emergence of the Arctic Basin as a theater of military operations for the world's two superpowers (see page 9). In addition, there is the strong desire on the part of some to wrest mineral resources from the Basin's icy grasp. Intertwined with the latter, the indigenous peoples of the Arctic Rim feel their traditional culture and hunting grounds are threatened by the intrusion of foreigners.

U.S. Interests

The research interests of the United States in the Arctic range from those related to national security, resource exploitation, and basic science to protection of the environment and preservation of the cultural heritage of indigenous populations. Activities in these and other areas of scientific interest have been funded by various federal agencies. Total government funding for arctic research in fiscal year 1985 was about $80 million. An additional unknown amount is spent by the oil industry in Alaska on environmental and other matters related to lease sales. A listing of these industry-sponsored research projects is maintained by the Lease Planning and Research Committee of the Alaska Oil and Gas Association. Descriptions of new projects are published in *Alaskan Update*, a publication of the Alaska Oil and Gas Association. Collectively, these proprietary studies must increase the total by many millions more. The $80 million government expenditure is probably understated because some federal activities in the Arctic are not regarded by the sponsoring agencies as research, and not all the logistics costs are accounted for in the $80 million total.

The only overall policy that guides U.S. interests in the Arctic is National Security Decision Directive (NSDD) 90, which was issued by the President of the United States in 1983. NSDD 90 establishes a broad arctic policy in four major areas. This policy is intended

> **1)** *to protect essential security interests, which interests shall include the preservation of the principles of freedom of the seas and superjacent airspace;*

2) to support sound and rational development in the Arctic with minimal adverse effects on the environment;

3) to promote scientific research in those fields that contribute to knowledge of the arctic environment, or scientific research that is arctic specific;

4) to promote mutually beneficial international cooperation to achieve the aforementioned goals.

NSDD 90 is actually a more recent version of two previous executive directives on U.S. arctic policy. The first of these, the National Security Decision Memorandum (NSDM) 144 of 1971, in addition to articulating broad policy guidelines similar to those in NSDD 90, also established the Interagency Arctic Policy Group (IAPG).

The second memorandum, NSDM 202, released in 1973, confirmed the earlier statement and reaffirmed the Administration's desire for the United States to pursue cooperative programs with other Arctic Rim countries in such areas as scientific research, resource development, and environmental protection. (Excellent discussions on U.S. arctic policy can be found in Westermeyer (1984) and Weller (1984). Both sources have been used freely in this article.)

Thus, in the period 1971–1983, three presidential statements spoke to U.S. arctic policy and created the IAPG, which was supposed to guide the implementation of the policy and coordinate the programs of the various federal agencies engaged in arctic research. The IAPG and the Interagency Arctic Coordinating Committee established at the request of the Department of State were unable to develop a comprehensive and coordinated arctic research program for the United States because there was no legally binding requirement to do so. Hence, the federal agencies, such as the Department of Interior, National Science Foundation, Department of Defense, and Department of Energy, continued to go to Congress with budget requests to support research programs that legitimately fell within their missions.

Because NSDD 90 was not an effective instrument for a coordinated approach to arctic research, the Congress passed the Arctic Research and Policy Act of 1984. The bill, introduced by U.S. Senator Frank Murkowski, Republican of Alaska, and cosponsored by Senator Ted Stevens, Republican of Alaska, and the late Senator Henry Jackson, Democrat of Washington, became law when it was signed by President Reagan on July 31, 1984.

This act creates two bodies—the Arctic Research Commission (ARC) and the Interagency Arctic Research Policy Committee (IARPC). These two bodies have separate but related responsibilities. In simplest terms, the Commission is charged with recommending a national arctic research policy, and the Committee has the responsibility of developing a comprehensive research plan to implement the policy. The act also requires the development of a single, unified multi-agency budget for arctic research. Ideally, this budget process should provide for a better coordinated research program that avoids duplication in programs of two or more agencies or gaps that have not been addressed by any agency.

The act does not provide for increased congressional appropriations. When an earlier version of the act was introduced in the Senate in 1982, it had a provision for a $25 million funding base that was supposed to have been in addition to funds appropriated for the various agencies. That provision did not prevail in the 1984 act and, given the budget climate in Washington that is likely to prevail for the next several years, the probability of an increase in non-defense arctic research is very low. Funding for new starts will most likely have to be carved from the existing total rather than being viewed as an add-on.

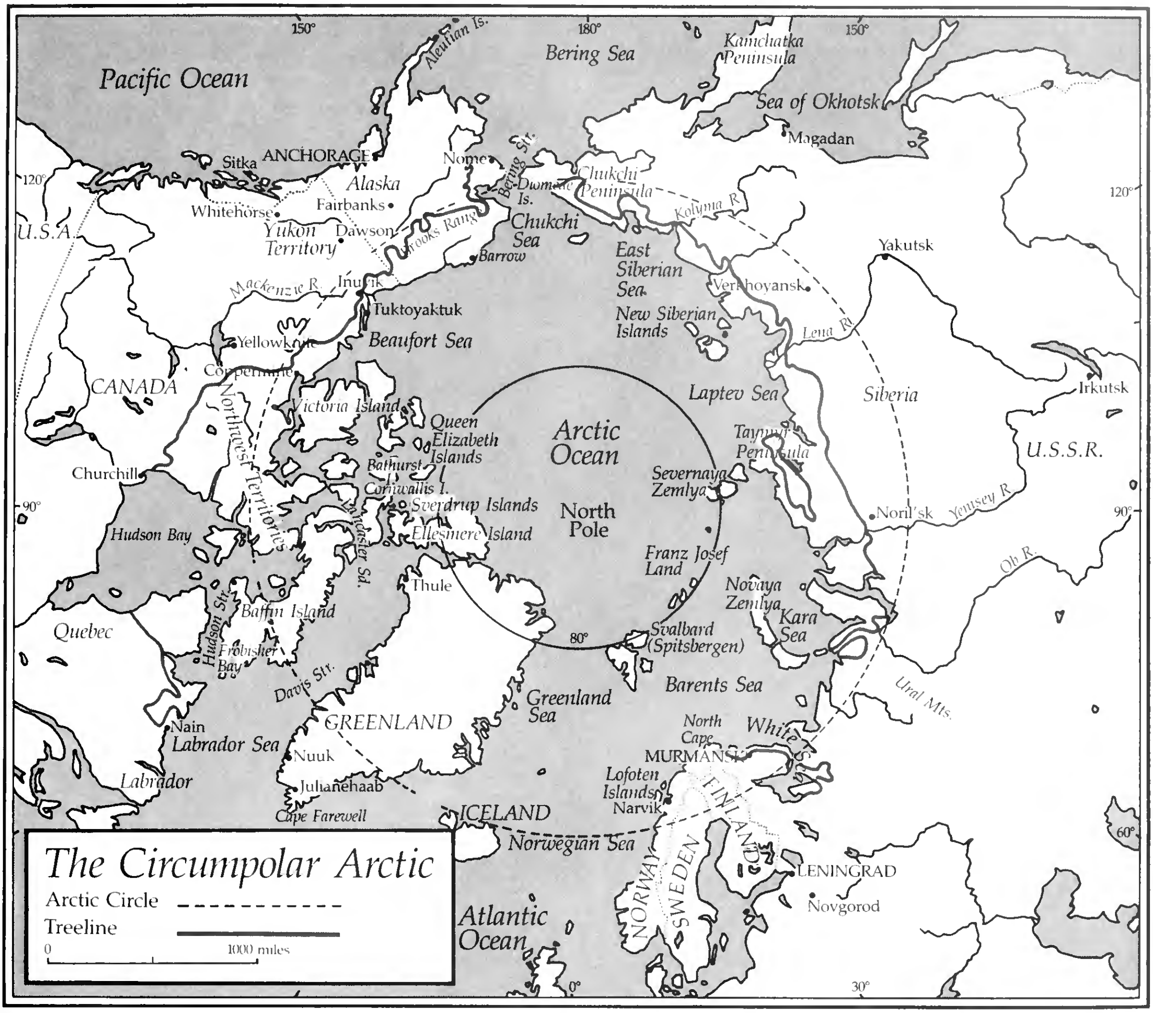
The prospect of level spending for arctic research for the remainder of the 1980s and beyond makes the need for a coherent research plan even more cogent. Priorities will have to be set not only within disciplines but also between disciplines. This difficult but necessary task will fall to the Commission.

The Commissioners were appointed by the President of the United States in early 1985 and sworn in at public ceremonies in Anchorage and Fairbanks on 1 March 1985. The act specifies the composition of the six Commissioners as follows: the Director of the National Science Foundation is automatically ex-officio; of the remaining five Presidential appointees, three must come from academic institutions, one is to be a representative of industry, and one must be an indigenous inhabitant of the Arctic. The leadership of the IARPC is lodged in the Division of Polar Programs of the National Science Foundation.

These guidelines led to the following appointments: Oliver Leavitt, a resident of Barrow, Alaska, is the native Alaskan Commissioner; Elmer E. Rasmuson of Anchorage, Alaska, is the representative of industry; and Juan G. Roederer of Fairbanks, Alaska, A. Lincoln Washburn of Seattle, and this author (Los Angeles) are the three representatives from academia. I am the Chairman and Roederer is Vice-Chairman. The Commission's office is in Los Angeles, and a branch office is now operational in Anchorage. The Executive Director is W. Timothy Hushen, who, for several years, has been the Executive Secretary of the Polar Research Board of the National Academy of Sciences in Washington, D.C.

The act defines the Arctic as ". . . all United States and foreign territory north of the Arctic Circle and all United States territory north and west of the boundary formed by the Porcupine, Yukon, and Kuskokwim Rivers; all contiguous seas, including the Arctic Ocean, and the Beaufort, Bering, and Chukchi Seas; and the Aleutian chain."

Those familiar with the Arctic will recognize that if this definition is followed rigorously, the southern fourth of Greenland would be excluded, and a large part of Siberia (mean air temperature in January about −44 degrees Celsius) would not be included. While there are a number of definitions of the Arctic, in almost any one other than a purely latitudinal definition, it is clear that the southern boundary of the Arctic will be south of the Arctic



Circle in some sectors and to the north in others.

With respect to the seas in the north polar regions, however, the act is very explicit. In addition to the Arctic Ocean itself, the term, "... all contiguous seas ...," includes not only the specifically identified Beaufort, Bering, and Chukchi Seas, but also, by inference, the Barents, Greenland, and Norwegian Seas, as well as Baffin Bay, the Davis and Denmark Straits, and at least the northern part of the Labrador Sea in the North Atlantic.

Dedicated Vessel Needed

There are many issues related to the marine sciences that the Commission will have to deal with. An exhaustive list is succinctly presented in "National Issues and Research Priorities in the Arctic," a 1985 publication of the Polar Research Board. The sections on Physical and Chemical Oceanography, Marine Life Sciences, and Arctic Engineering should be read by all those with a serious interest in research in the arctic marine environment. Among the research needs cited in that document are the needs for an ice-strengthened research platform, engineering studies related to offshore platforms in the Arctic Basin, marine transportation of crude oil in ice-infested waters, the fate of crude oil spills in pack ice, and the impact of exploration for, and exploitation of, offshore crude oil on the habits of the bowhead whale. This is by no means an exhaustive list, nor are the various issues listed here in order of priority, but from the public testimony presented to the Arctic Research Commission by interested parties in Alaska (Barrow, Fairbanks, and Anchorage) in June 1985, it is clear that these issues are among those that are of more than passing concern or academic interest to those who are concerned about research in the Arctic Basin and adjoining seas.

Although it is impossible to say at this writing what level of priority will be given by the Arctic Research Commission to the acquisition of an ice-strengthened research vessel, it seems apparent to this writer that one can hardly argue for an increased level of U.S. research in arctic waters, either applied or basic, without considering the need for a dedicated research platform flying the American flag. U.S. Coast Guard icebreakers have been used for scientific purposes in both the Southern Ocean and the Arctic Ocean for several decades (see page 47). But icebreakers are designed primarily to break ice. Their basic mission is a logistical support function and not scientific research. One should be quick to acknowledge, however, that when called on to function as research platforms, the icebreakers of the

Alaskan native fishes for cod in the Chukchi Sea. (Photo by Phyllis McCutcheon, Photo Researchers)

U.S. Coast Guard and their crews have responded within the limits of their ability and equipment. Serious and sustained marine research by U.S. scientists in polar seas, however, will not materialize unless a dedicated research vessel is made available.

Offshore Oil and Gas Development

Arctic oil exploration has moved offshore into the Beaufort, Chukchi, and Bering Seas. The Beaufort Sea presents a problem for year-round drilling in ice-covered waters deeper than 20 meters. Whereas artificial islands are cost effective in shallow waters, they are not practical in deeper waters. For obvious reasons, cost effectiveness is increased when a drilling platform can be used 12 months a year, and moved from one site to another. Artificial islands, or some variation thereof, provide reasonable protection of the drill rig and related equipment from the ice pack, which is in constant motion. Drill ships, such as the ones used in deeper waters off the McKenzie Delta, can operate only during the summer when the pack ice has dissipated.

The newest technology in drilling rigs for arctic offshore operations is based on the concept of relocatable structures or mobile drilling units (MODU) that rest on the seafloor while in operation, but can be floated to a new location. One MODU is already in use in the Beaufort Sea about 20 kilometers off the coast of Alaska in 15 meters of water. Built by Global Marine, this Concrete Island Drilling System (CIDS) is a prototype that supported a successful drilling program for Exxon in 1984 and will be on a new site in 1985.

For drilling in deeper water in ice-covered seas, the Ocean Drilling and Exploration Company has designed a conical monopod of steel capable of operating year-round in water up to 60 meters deep. These new generation platforms are designed with the benefit of extensive research on models under simulated ice conditions. The high costs of drilling in arctic waters is now regarded as a major factor in determining the economics of exploration.

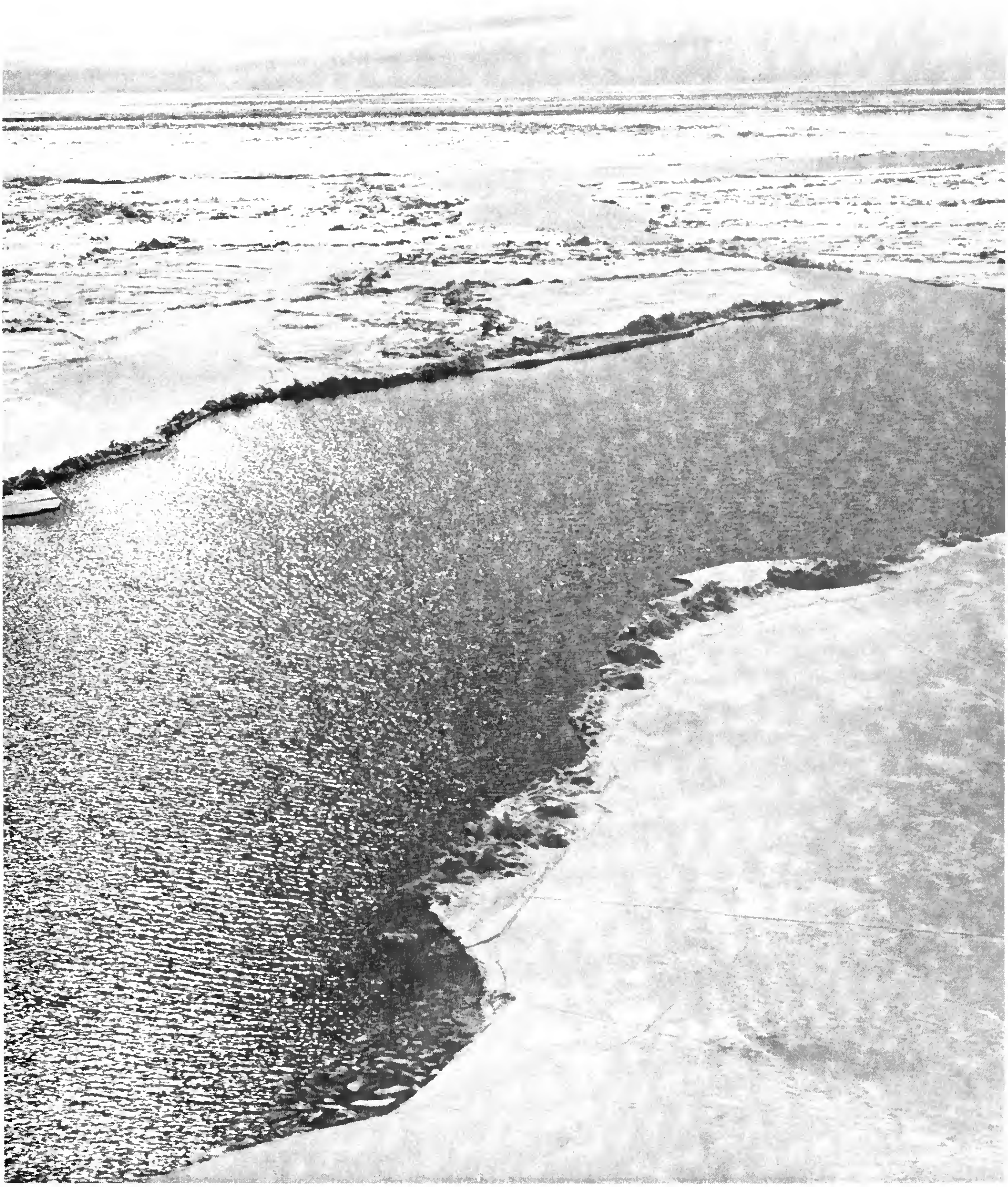
Whereas the huge exploration and developmental costs of bringing in the Prudhoe and Kuparuk fields of the Alaska Coastal Plain were offset by the enormous reserves involved, future offshore discoveries are unlikely to be of the same size. Hence, exploratory drilling costs are much more sensitive in current operations than they were in the past.

The Mukluk dry hole in Harrison Bay off Arctic Alaska is estimated to have cost $140 million, and is a dramatic example of the capital intensive nature of the oil industry. Certainly any cost reduction measures derived from research in all fields related to arctic offshore operations will be welcomed by the oil industry. For a good summary of industrial research and development in new platforms for drilling in the pack ice off the Arctic Coast of Alaska, the reader is directed to the special edition of the *Oil and Gas Journal* dedicated to this subject which is listed in the references at the end of this article.

Once oil is discovered in producible quantities in offshore arctic reservoirs, it must be transported to market. Whether this is accomplished by tanker or pipeline will depend not only on the economics of one or the other method, but also on the environmental reliability of each. The voyage of the *Manhattan* in 1969 from Philadelphia to Barrow via the Northwest Passage proved that tanker traffic is a viable means of moving arctic-produced crude to market, at least during the summer months. Indeed, the major impediment to tanker traffic through the Canadian archipelago may be political rather than physical. On September 10, 1985, sixteen years after the *Manhattan*'s epic voyage, another ship, *Imperial Bedford*, delivered 100,000 barrels of crude oil from Panarctic Oils, Ltd., in the Canadian Arctic Island to a refinery in Montreal. The voyage of 5,400 kilometers took three weeks, and is the first of additional shipments planned for the next several years. As marine transport of oil increases, the forecasting of weather and ice movement will be crucial to safe passage of these tankers along the coastal regions of both Canada and Alaska. There is still room for considerable research in these areas for which a variety of images from polar-orbiting satellites will play increasingly important roles.

Transportation by pipeline traversing permafrost terrains is an accomplished fact in the 1,300-kilometer pipeline from Prudhoe Bay to Valdez, Alaska. Pipelines on the seafloor of the Arctic Ocean are a different matter, however. Pressure ridge keels in sea ice are known to gouge the seafloor, and any pipeline laid on it must be buried below the depth of expected gouging. Research on the distribution, depth, frequency, and occurrence of the gouges is crucial to the design of undersea pipelines not only to prevent their rupture, but also to keep their costs reasonable. The cost of over design (for example, burying a pipeline 5 meters when 3 would suffice) could more than pay for research on the frequency and occurrence of gouges.

Another problem encountered with buried



The arctic ice cover is constantly shifting in response to winds, waves, and currents. Understanding the movements of the ice, as well as other aspects of arctic oceanography, must be a high priority. Above, an opening, known as a lead, in the ice cover some 50 kilometers off Point McIntyre, Alaska. (Photo by J.C. LaBelle, Arctic Environmental Information and Data Center).

The ice-covered horizon of Alaska's Bering Sea. (Photo by G. Carleton Ray, Photo Researchers)

pipelines on the arctic seabed is the presence of sub-sea permafrost. Research on this phenomenon will be useful not only on pipeline design, but also on drilling techniques and well completion in offshore sites.

It is clear from testimony presented to the Arctic Research Commission by Inuit residents of Barrow, Alaska, that the economic and cultural impact of resource exploration and exploitation on native arctic populations in the Western Beaufort Sea is a matter that cannot be ignored or dealt with in a casual manner by industry.

Foremost among the concerns of the Barrow group is their ability to continue hunting the Bowhead whale (see page 81). As energy development progresses to offshore sites, the Eskimos are interested in the impact such activities will have on the migratory habits of these marine mammals. Industry has done some research on this question, but the impact drilling and production activities and potential marine transport will have on the bowhead is virtually unknown. Clearly, this is an area of research that is paramount in the eyes of those who have hunted the bowhead for centuries, and is a matter that will require attention.

There are a number of other areas of research in the arctic marine environment that have not been addressed in this introduction or in this issue of *Oceanus*. The reader should not infer that such areas are not important simply because they have not been mentioned here. The basic purpose of this statement is to provide an indication of the magnitude of the task faced both by the Arctic Research Commission and the Interagency Arctic Research Policy Committee. As both groups continue to evaluate the research needs in the whole range of problem areas, it is hoped that a list of priorities will emerge that relate to an overall U.S. research policy for the Arctic. The success of this endeavor will depend on the diligence with which the Commission and the IARPC pursue their goals, the testimony of the research community and other interested parties, plus the collaborative efforts of the federal government, the State of Alaska, and industry. This is a formidable, but not impossible, task.

James H. Zumberge is President of the University of Southern California and Chairman of the Arctic Research Commission.

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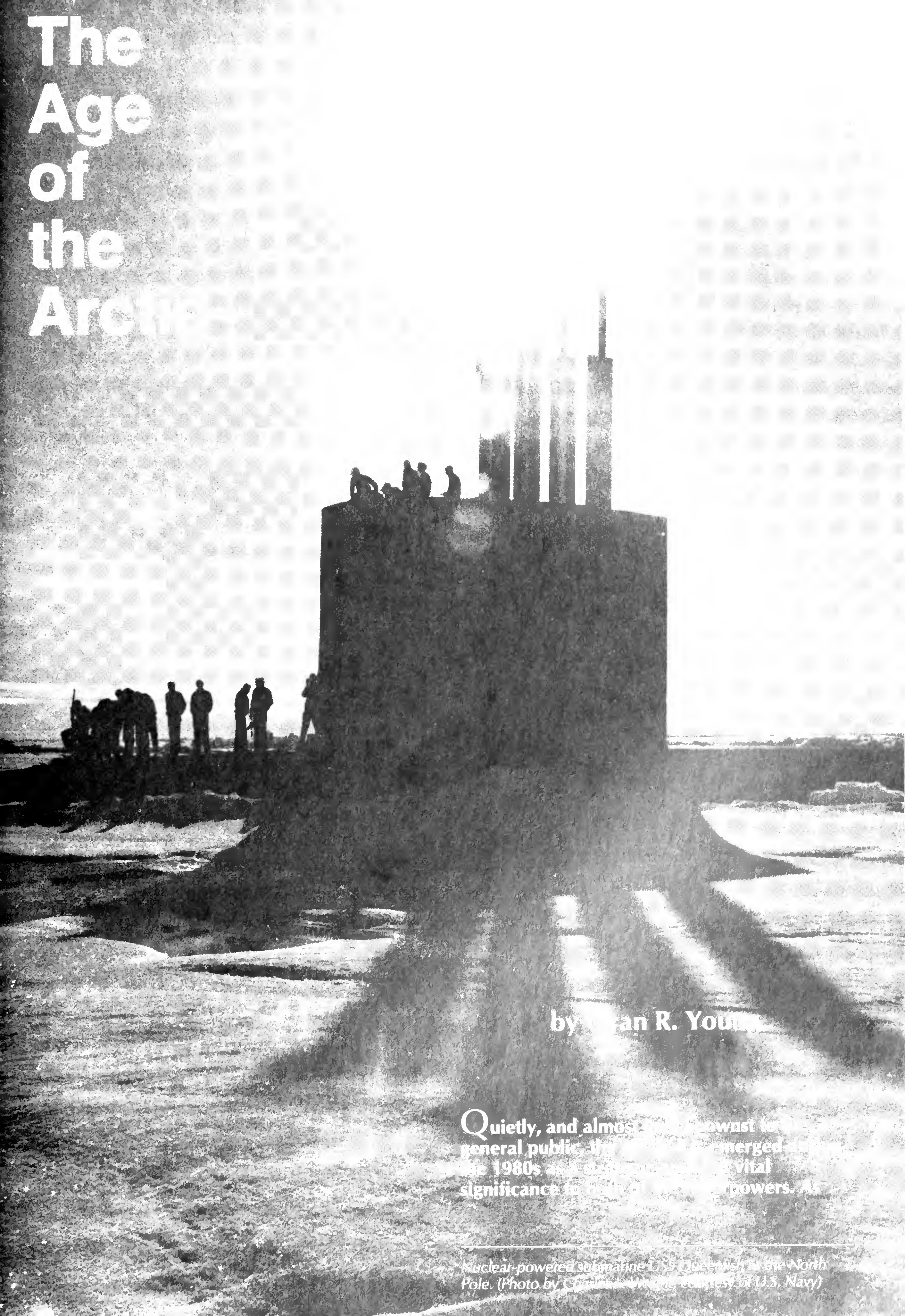

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Nuclear-powered submarine U.S.S. Queenfish at the North Pole. (Photo by [illegible], courtesy of U.S. Navy)

EDITOR'S NOTE: This article is adapted with permission from the Winter 1985–86 issue of *Foreign Policy* magazine, published by the Carnegie Endowment for International Peace. It contains added material not in the *Foreign Policy* article.

recently as 1981, political scientist Lincoln Bloomfield of the Massachusetts Institute of Technology could present a comparatively benign view of the Arctic, arguing that the region was free of major international conflicts. Thus, he suggested, the Arctic might make an attractive laboratory for certain kinds of international cooperation. Today, however, the Arctic is rapidly becoming a focus for defense and development issues that touch on the core interests of each of the superpowers. Although this change has intensified the need for cooperative arrangements in the region, it has greatly complicated this task as well.

Two trends are largely responsible for the Arctic's dramatic transformation. Recent developments in military technology are rapidly turning the Arctic into one of the world's most active and important areas of military operations; the Arctic is no longer merely a frozen wasteland over which ballistic missiles would fly in wartime. The Far North also is rapidly industrializing and therefore becoming critically important to U.S. and Soviet security. And

The world is entering the age of the Arctic, an era in which those concerned with international peace and security will urgently need to know much more about the region.

some planners are questioning the security of the Arctic's key industrial installations—for example, the Prudhoe Bay oil complex and the trans-Alaska oil pipeline—rather than only thinking about the use of the Arctic as a battlefield or site for military bases.

It is hardly an exaggeration to say that the world is entering the age of the Arctic, an era in which those concerned with international peace and security will urgently need to know much more about the region. The Arctic has always possessed a certain inherent strategic significance. It is hard to ignore that the United States and the Soviet Union are immediate neighbors in the Arctic (western Alaska and eastern Siberia are only 57 miles apart at the Bering Strait), that the shortest route between the two superpowers is across the North Pole, and that both superpowers front directly on the Arctic Basin. (The Soviet Union alone controls about half of the arctic littoral.) The Arctic's strategic significance stems in part from more specific factors like the Greenland-Iceland-United Kingdom (GIUK) Gap. This gap, consisting of the Denmark Strait and the Norwegian Sea, represents the main outlet to the open ocean for vessels of the Soviet Northern Fleet based on the Kola Peninsula, and therefore is a front line of NATO defenses.

Technology and Military Strategy

Technology has played a major role in the increasing importance of the Arctic, too. With the increased vulnerability of land-based missiles, submarine-launched ballistic missiles (SLBMs) have loomed larger and larger in superpower strategic calculations. At the same time, recent improvements in the capabilities of ballistic missile nuclear submarines (SSBNs), as well as in SLBM range and accuracy, have enhanced dramatically the attractions of the Arctic Ocean as a theater for seaborne strategic-weapons deployment. Already, Soviet SS-N-8 and SS-N-18 missiles mounted on Delta-class submarines can reach virtually every major military target in North America and Western Europe without leaving arctic patrol stations. Similarly, American Trident submarines carrying C-4 missiles can attack military targets throughout the Soviet Union from arctic waters.

The latest generations of SSBNs, the Soviet Typhoon-class submarine and the American Ohio-class submarine, are even more effective. The Typhoon is designed specifically for operations in ice-covered waters, but any modern SSBN can perform its mission in the Arctic Basin. There are numerous points under the polar ice pack where all modern submarines can break through to the surface to fire their missiles. The ice pack is also frequently interrupted by large stretches of open water. The newest SSBNs are or soon will be equipped with the most advanced operational missiles, such as the 6–9-warhead Soviet SS-N-20, the even newer SS-NX-23, and the American Trident II (also known as the D-5), with 8–10 warheads (see *Oceanus*, Vol. 28, No. 2, for an analysis of the Trident capability). These missiles each have a range of more than 5,000 miles and are nearly as accurate as land-based missiles. Further, Arctic-based SSBNs are peculiarly difficult to detect, much less to track closely. The ambient noise generated by arctic ice reduces dramatically the effectiveness of acoustic monitoring methods such as sonar devices, while the opaqueness of the ice prevents most visual monitoring.

Moscow has moved vigorously to exploit these military attractions of arctic waters. Well over one-half of all Soviet SSBNs are stationed with the Northern Fleet at Severomorsk on the Kola Peninsula. These submarines actively roam the Arctic Basin, constituting a virtually invulnerable strategic force capable of launching increasingly accurate missiles against Western targets without making any effort to evade NATO defenses along the GIUK Gap or even to leave their arctic haven. These vessels can also travel between Severomorsk in the European Arctic and Petropavlovsk Kamchatskiy in the northern Pacific largely under cover of arctic ice.

The United States does not have an arctic base comparable to Severomorsk. Yet American missile submarines based in Bangor, Washington, are fully capable of operating in arctic waters for extended periods. The United States also is rapidly expanding its fleet of Ohio-class submarines and is fitting these vessels with Trident II missiles. Although the details are classified, private conversations with high-ranking Pentagon officials indicate that

American SSBNs are increasingly active in the Arctic and that the United States is not far behind the Soviet Union in this realm. As Soviet antisubmarine warfare capabilities increase and American SSBNs seek the greater security of arctic waters, the Far North is likely to become the world's most important base for seaborne strategic-delivery systems.

The region also provides new possibilities for highly accurate air-launched cruise missiles (ALCMs). Already, long-range sea-launched cruise missiles with 2,000-mile ranges are carried by submarines able to prowl the Arctic. The potential for deploying long-range ALCMs suitable for stand-off attacks initiated from the Arctic is even more important. The United States already has equipped five squadrons of B-52G bombers (that is, 98 aircraft) with a total of 1,150 long-range cruise missiles and plans to add 600 more ALCMs to its inventory. Work is also proceeding on the Advanced Cruise Missile, of which as many as 1,500 air-launched models may be deployed. Although somewhat behind the United States in this field, the Soviet Union apparently is deploying long-range ALCMs on Backfire and Bear-H bombers. By the end of the decade, each superpower is expected to have a substantial force of long-range ALCMs mounted on the latest generations of high-endurance bombers, notably the 4,600-mile-range American B-1B and Moscow's 4,500-mile-range Blackjack-A.

Such ALCM deployment again puts the military spotlight on the Arctic. The great circle route across the North Pole remains the shortest pathway between North America and the Soviet Union. Long-range ALCMs launched from high-endurance bombers operating over the Arctic will be able to reach virtually any important military target in North America and Western Europe as well as the Soviet Union. Both superpowers will thus be able to initiate stand-off nuclear strikes against enemy targets from comparatively safe launch sites. They may also be able to implement policies that can avoid or minimize the political complications arising from basing ground-launched cruise missiles on their allies' soil. Additionally, the Arctic itself is an ideal environment for cruise-missile-equipped bombers. Its vastness and sparse population permit military activities to be carried out largely unnoticed. Arctic ionospheric irregularities also can interfere with the use of over-the-horizon-backscatter (OTH-B) radars designed to track high-endurance bombers.

Not surprisingly, these developments in offensive systems have greatly heightened interest in Arctic-based defenses. Conventional naval vessels confront major difficulties in patrolling ice-filled arctic waters. And the Arctic's pack ice and marginal ice zones provide a shield for SSBNs from satellites and aerial surveillance and from acoustic devices stationed on the seabed. Only nuclear-powered attack submarines seem up to the job, and despite the great expense, both Washington and Moscow already seem to be assigning many of these vessels to monitor their missile-packed counterparts.

ALCM deployment has already stimulated renewed interest in arctic air defenses. In North America, the 30-year-old DEW (Distant Early Warning) line, which was allowed to become obsolete, is now being modernized. The improved version, known as the North Warning System, will include, upon completion in 1992, at least 52 sites strung along the 70th parallel, equipped with both microwave radars and OTH-B radars.

Two additional factors round out this picture of the Arctic as a major strategic theater. Arctic skies are filled with natural phenomena, such as the aurora borealis and electromagnetic storms, that are capable of jamming communications and defense systems. These conditions can help protect Arctic-based retaliatory forces like bomber-carried ALCMs or SLBMs. But atmospheric disturbances can also interfere with cruise missile (but not ballistic missile) guidance systems, as well as with communications with nuclear missile submarines. To the extent that military use of the Arctic continues to grow, military planners will have to redouble their efforts to solve the region's unique communication, command, and control problems.

Finally, the construction and protection of vitally important industrial facilities have added yet another dimension to the militarization of the Arctic. The Prudhoe Bay and Kuparuk oil fields on the North Slope of Alaska, for example, currently account for approximately 19 percent of U.S. oil production and 11 percent of U.S. oil consumption. Both the oil fields and the trans-Alaska pipeline system used to move the oil to southern markets are highly vulnerable targets, as are the burgeoning industrial installations in Siberia. The Urengoy natural gas field, slated to become a critical factor in the Soviet energy equation, and the Soviet Siberian gas pipeline, which runs 2,750 miles from northwestern Siberia to the Czech border, would be obvious targets in any effort to disrupt the Soviet economy. With U.S. and Soviet dependence on secure supplies of energy and other arctic raw materials virtually certain to increase, efforts to defend these industrial installations undoubtedly will expand as well.

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Foreign Policy and the Arctic

Barring highly improbable achievements in the realm of strategic defense, the Arctic's growing strategic significance will hardly facilitate proposals to use the region as a laboratory for superpower cooperation. The fact that the Arctic's significance is only now becoming fully apparent will greatly complicate arms control efforts. Both Moscow and Washington undoubtedly will want to explore the region's full military potential before considering any restrictions on strategic weapons and other hardware. Thus, prospects currently are not bright for declaring the Arctic a nuclear-free zone, as often urged by groups like the Inuit Circumpolar Conference, a transnational organization of indigenous arctic peoples.

The growing military role of the Arctic can also only heighten sensibilities regarding jurisdictional issues in the region. This is true of peripheral disputes such as the U.S.-Canadian and Soviet-Norwegian disagreements over the Beaufort Sea and Barents Sea boundaries, respectively, as well as of controversies directly involving the superpowers, such as demarcating the maritime boundary in the Chukchi Sea, which was left unspecified in 1867, when the United States bought Alaska from Russia. No one can rule out the possibility of international cooperation among various arctic rim states in specific functional areas—for example, environmental protection or scientific research. But the region can no longer be seen as a promising, Antarctica-like laboratory for superpower collaboration by virtue of its remoteness and relative insignificance.

What ultimately drives arctic industrialization, however, is the promise of secure access.

The militarization of the Arctic also carries more specific political implications for each superpower. The major U.S. concerns center on relations with northern allies such as Canada, Denmark, Greenland, Iceland, and Norway, and Washington is currently making a concerted effort to accelerate arctic security cooperation. In early 1985, the United States and Iceland agreed to build two new radar stations on the island to monitor Soviet sea and air traffic in the Arctic. In addition, American officials have worked hard to maintain Norway's commitment, however ambivalent, to NATO, as well as to establish good relations with the Home Rule government in Greenland, the political system established in 1979 in recognition of the island's growing autonomy from Denmark. At the same time, the triumph of Canadian Prime Minister Brian Mulroney's Progressive Conservative party in 1984 has substantially helped U.S.-Canadian ventures. The North Warning System is a fully cooperative venture, and the two countries collaborated on the North American Air Defense Master Plan within the context of the reorganized and expanded North American Aerospace Defense Command (NORAD).

Yet the Arctic's militarization may also greatly increase friction between the United States and its northern allies, especially Canada. Washington put heavy pressure on Ottawa to accept the testing over northern Canada of ALCMs without nuclear armaments, and former Prime Minister Pierre Trudeau's eventual concurrence triggered an outpouring of protest by the Canadian public. Canadian tempers are also flaring over the fact that U.S. icebreakers and nuclear submarines are actively plying the waters of the Canadian arctic archipelago, including the waters of the Northwest Passage, the sea route between Europe and the Far East. As part of its general unwillingness to acknowledge Canadian sovereignty over these waters, Washington does not seek explicit permission for transits by these vessels. The recent voyage through the Northwest Passage of the U.S. icebreaker *Polar Sea* has motivated Canadian policymakers to consider submitting Canada's claims to sovereignty in the Arctic to the World Court. In addition, many Canadians fear that the new U.S.-Canadian air-defense system might commit Canada to accept the stationing of U.S. weapons on Canadian territory.

More generally, influential Canadians often fret about any prospect of increased American military activity in the Arctic. Although each individual initiative may take the form of a cooperative U.S.-Canadian venture, Canada lacks the military capabilities to participate as an equal partner in such arrangements.

The Soviet Union borders on about half of the Arctic Basin and is undoubtedly the Arctic's leading power. Thus the Soviets can move confidently into the age of the Arctic without any concern about relations with northern allies. Objectively, the expansion of Arctic Basin military operations as such must reduce, from Moscow's vantage, the strategic importance of the GIUK Gap. The Soviets are reaching a point where they will not need to move strategic-delivery vehicles through the passage in order to hit European and North American targets.

At the same time, the Arctic's burgeoning military-strategic importance will inevitably heighten Soviet sensitivities regarding regional jurisdictional issues. Moscow will perceive increased incentives to claim the Barents, Kara, Laptev, and East Siberian Seas as internal waters or closed seas in order to secure access to the central Arctic Basin for Soviet submarines, to maximize cover for submarines in the marginal ice zones along Siberia, and to protect industrial installations along the northern coasts of Siberia. The Soviets undoubtedly will do whatever they can to promote the idea that the Arctic Basin is fundamentally a Soviet lake.

Arctic Industrialization

The Arctic's natural wealth is immense and has already given developers plenty of incentive, despite high production and delivery costs stemming from harsh natural conditions and huge distances. What ultimately drives arctic industrialization, however, is the promise of secure access. No price or supply manipulations like those of the Organization of Petroleum Exporting Countries (OPEC) are going to disrupt supplies of arctic raw materials. Industrialization not only adds greatly to the strategic significance of the Arctic, but also contributes to the region's militarization, as planners become more concerned about defending these facilities.

Although the image of a "great arctic energy rush" may be premature, the exploitation of hydrocarbons has clearly fueled arctic industrialization. Estimates suggest that the Arctic's potentially recoverable reserves of crude oil range between 100 and 200 billion barrels and that its potentially recoverable natural gas deposits may approach 2,000 trillion cubic feet. By comparison, OPEC's proven reserves of crude oil approach 440 billion barrels, while U.S. gas potential (excluding Alaska) is estimated at 492 trillion cubic feet of natural gas.

The Prudhoe Bay field on Alaska's North Slope alone, discovered only in 1968, originally contained an estimated 9–10 billion barrels of recoverable oil and 26 trillion cubic feet of recoverable natural gas. It is the largest single field ever discovered in the United States. Today, 1.6–1.7 million barrels of oil are produced daily at Prudhoe Bay and the adjoining Kuparuk field and are shipped to southern markets through the Alaska pipeline. Some estimates put additional recoverable reserves of oil in the North American Arctic at 50 billion or more barrels. The region's recoverable reserves of natural gas amount to more than 300 trillion cubic feet, though lack of a transportation system has so far prevented commercial exploitation.

While the oil reserves of the Soviet Arctic are probably not as large as those of the North American Arctic, western Siberia's natural gas reserves may amount to 500 trillion cubic feet. The Urengoy field alone has reserves of 212 trillion cubic feet; production from this field was scheduled to reach 9 trillion cubic feet in 1985. The rapid development of this gigantic gas field, combined with preparations to extract natural gas from the lower Ob River basin, undoubtedly explains much of the inaccuracy of Western predictions during the late 1970s that the Soviet Union would become a net energy importer in the 1980s.

The Arctic's energy potential is hardly confined to oil and natural gas. Northern Alaska's coal reserves may approach 4 trillion tons—equaling the total of the entire lower 48 states. Some analysts believe that Siberia contains as much as 7 trillion tons of coal.

Recently, the Far North also has become a site for large-scale hydroelectric power production. In Canada's Quebec province, the James Bay Project, initiated during the 1970s, has begun to come on line. Phase 1 is designed to provide 10,300 megawatts of power, and phase 2 will add another 3,400–5,000 megawatts. By the year 2000, the energy equivalent of 25 to 30 nuclear power plants will flow southward from the project's generators. The political renaissance of Robert Bourassa, the father of the James Bay Project, ensures that the theme of "power from the North" will continue to be politically potent in Canada for years. Powerful interest groups are pressing to construct several dams on the Watana-Devil Canyon segment of Alaska's Susitna River to spur the industrialization of the Anchorage-Fairbanks corridor, through which the state's main railroad runs. Many of the northern rivers of Scandinavia have already been dammed to generate hydroelectric power, and at least eight large hydroelectric power stations are currently operating in Siberia.

The nonfuel mineral reserves of the Arctic constitute yet another stimulus for industrialization. The iron ore deposits of Scandinavia and of the Kola Peninsula in the Soviet Union have been mined for some time. The lure of minerals like gold, copper, and tin has helped stimulate the Soviet drive to industrialize central and eastern Siberia. Alaska's Red Dog deposit, 180 miles north of Nome, contains an estimated 85 million tons of ore, consisting of more than 17 percent zinc, 5 percent lead, and 2.4 ounces of silver per ton. This world-class lode has an in-the-ground value of more than $11 billion at 1983 prices.

Not surprisingly, all of this industrial activity has produced a dramatic expansion of northern transportation systems. The Alaska pipeline, constructed at a cost of $8–$9 billion in 1974 dollars, carries approximately 1.7 million barrels of oil daily from Prudhoe Bay to Valdez, an ice-free port more than 800 miles to the south. The Soviet Siberian gas pipeline, an $18 billion project, is now becoming operational. Today, governments, businesses, and citizens in the north face the task of comparing relative merits of alternative pipeline systems designed to transport natural gas from northern Alaska and the Canadian Arctic to southern markets.

The actual and potential environmental hazards of industrial development in the Far North are severe.

Arctic waters may become another vital transportation network. The Soviet Union is currently able to keep the Northern Sea Route, a commercial artery stretching some 1,700 miles along the Soviet Arctic coast, open up to 150 days a year with the aid of the world's largest fleet of nuclear-powered ice-breakers (see page 47). There is serious interest among some oil companies in opening up all or part of the Northwest Passage to the shipping of natural resources from the Arctic, despite intimidating engineering challenges and environmental hazards. The passage is also several thousand miles shorter than alternative routes between Europe and Japan, including the one through the Panama Canal. Yet both pipelines and shipping are easily disrupted and therefore worrisome to military planners.

Rapid industrialization inevitably generates unintended side effects that give rise to major policy issues, and arctic development is no exception. The actual and potential environmental hazards of industrial development in the Far North are severe, partly because arctic development must generally proceed on a mammoth scale to be commercially viable, and partly because certain key arctic ecosystems are so fragile (see page 36).

Additionally, recent research has demonstrated the importance of the Arctic to the entire global physical system. As Lisle A. Rose, then a polar affairs specialist for the State Department, wrote in the June 1982 issue of *Arctic*, the region's " 'heat budget' created by the interaction of ocean, sea ice, and atmosphere" is a major determinant of climatic change. Thus consequences of arctic industrialization could spread far beyond the pole. During the 1970s, concerns expressed by environmentalists led to major revisions in the original plans for the Prudhoe Bay complex and the Alaska pipeline system. Many more such battles between industrial and environmental interests are sure to be fought.

In sharp contrast to the Antarctic, the Arctic is a homeland as well as a frontier. Its indigenous peoples have legitimate claims, rooted in rights of use and occupancy, to large segments of the polar region and its natural resources. Although most of the Arctic is nominally included in the public domains of the rim states, unresolved claims of various indigenous groups cast a long shadow over legal titles in the region and greatly concern potential developers. The desire to extract the oil of Prudhoe Bay undoubtedly spurred the passage in the United States of the Alaska Native Claims Settlement Act of 1971. The central feature of this act is that it extinguishes all remaining aboriginal claims to title in Alaska in exchange for a land and cash settlement. Similar deals may be necessary throughout the Arctic.

The native peoples of the Arctic are few, but development is still destined to generate a steady stream of controversies . . .

But rapid industrialization also poses numerous threats to the cultural integrity of indigenous communities scattered throughout the circumpolar north. Further, these peoples are quickly grasping the importance of protecting their cultures. Paradoxically, the industrialization process itself is giving them the wherewithal to resist threats to their ways of life, and larger publics to the south are beginning to take an interest in the welfare of these peoples. The native peoples of the Arctic are few, but arctic development is still destined to generate a steady stream of controversies concerning their place in a world full of advanced industrial societies.

Yet, while conflicts over the use of arctic resources will become both more common and more severe, neither the legislative nor the adversary processes typically employed to settle disputes in modern societies are well suited to handle such problems. The relevant interest groups are anything but equal in terms of influence in legislative arenas, and adversary processes regularly bog down in repetitious lawsuits that fail to settle the underlying issues at stake. The creation of an Arctic Resources Council might help in dealing with this problem. The Council, a private-sector organization, would promote the use of alternative techniques of dispute resolution, such as mediation and problem solving, in settling Arctic resource conflicts.

Arctic industrialization also accentuates the region's international character, partly because the discovery of vital natural resources has intensified jurisdictional conflicts. So long as the Arctic was a distant region of interest only to a handful of explorers, scientists, and native peoples, there was no pressing reason to clarify fuzzy international boundaries. Today, however, the delineation of the mineral-rich geologic structures forming the Navarin Basin in the central Bering Sea has heightened Soviet and American sensitivities about demarcating the Bering seabed. The discovery of hydrocarbons has intensified the U.S.-Canadian disagreement regarding their common maritime boundary in the Beaufort Sea. A similar controversy has emerged between Norway and the Soviet Union in the Barents Sea. The status of the continental shelf surrounding the Svalbard archipelago has become a contentious issue between Norway and several of the other parties, including the Soviet Union, to the Svalbard Convention of 1920, an international agreement providing for open access to the islands' natural resources while awarding sovereignty to Norway.

Yet powerful incentives for international cooperation in certain functional areas have emerged as well. Arctic haze and water pollution cannot be controlled without a coordinated effort by the arctic rim states. A compelling case can be made for establishing cooperative regimes to deal with arctic shipping and for protecting the Far North's marine mammals. Growing military concerns will hamper attempts to include both the United States and the Soviet Union in such arrangements. But significant progress has been made recently on several fronts.

The protective regime for polar bears, negotiated by Canada, Denmark, Norway, the Soviet Union, and the United States in 1973, has worked well and may be followed by similar arrangements for other migratory mammals, such as caribou, fairly soon. The agreement providing for joint decision making and coordinated monitoring for the Baffin Bay–Davis Strait area, which Canada and Denmark/Greenland signed in 1983, constitutes an important step toward handling responsibly the effects of industrial development in the eastern segment of the North American Arctic. Recently, prominent Canadians and Americans from both the private and the public sectors have suggested the creation of a similar U.S.-Canadian regime for the Beaufort Sea area. Moreover, in 1977, the indigenous peoples of the Arctic formed the Inuit Circumpolar Conference, a transnational organization recognized formally by the United Nations as a nongovernmental organization and dedicated to a cooperative search for arrangements to protect the region's natural and social systems.

Strategic stabilization and arms control issues must head any policy agenda.

The Arctic Policy Agenda

Strategic stabilization and arms control issues must head any arctic policy agenda. Is the region's militarization strategically stabilizing, enhancing the credibility of deterrence policies based on the idea of mutual assured destruction? Or is this trend a destabilizing factor, either because it extends the strategic arms race into a largely unknown and potentially volatile arena or because it adds to the incentives of the superpowers to abandon existing limitations on strategic-delivery vehicles? For reasons outlined earlier, the establishment of an arctic nuclear-free zone at this time will go nowhere. Yet more modest arms control initiatives might work. Two examples are, first, a ban on permanent deployment of nuclear weapons in the Arctic and on the use of nuclear devices for nonmilitary purposes in the region, and second, limits or rules for testing cruise missiles or other strategic-delivery vehicles in the Arctic, for minimizing the danger of incidents involving nuclear submarines, and for restricting the use of the Arctic for military exercises involving low-flying combat aircraft. Arrangements along these lines could prove mutually beneficial by limiting the region's militarization or by stabilizing the arctic military balance without interfering with either superpower's strategic freedom of action.

Almost equally important is developing a set of industrial policies for the Arctic. Specifically, are the national interests of the western arctic states in the resources of this region so great that political rather than commercial considerations should largely govern their development? Should governments rush to develop arctic energy resources, or should they keep these resources in reserve while more convenient supplies are exploited and more advanced technologies to deal with arctic conditions are perfected? Should the American and Canadian governments directly or indirectly subsidize the construction of arctic industrial facilities—for example, the proposed Arctic Natural Gas Transportation System—where such projects are politically desirable but commercially risky? Should Washington continue to ban nearly all exports of Alaskan crude oil to Japan and other foreign consumers? What would constitute a proper balance between arctic industrialization and the protection of key arctic ecosystems? Are the indigenous peoples of the Arctic entitled to a major voice in decisions concerning the region's industrialization?

A third range of arctic policy issues arises from linkages between militarization and industrialization. Does the emergence of the Arctic as a major military theater make it more or less attractive to resource developers? Will the regular use of the Northwest Passage by nuclear-powered submarines affect plans to use the waterway as a commercial shipping route? Will the efforts of military planners to solve arctic transportation and communication problems yield valuable nonmilitary spin-offs? Conversely, is the growing militarization of the Arctic likely to interfere with research needed to make arctic industrial operations both feasible and efficient? Clearly, the Far North's militarization and industrialization are closely related and need to be carefully coordinated. Tradeoffs are inevitable.

Two broader sets of concerns should figure prominently in discussion of these arctic policy issues. First, the Arctic, unlike most of the rest of the world's land, is owned outright by governments. And its marine areas are subject to their exclusive authority. The military use of this sparsely populated region is obviously subject to the control of public-sector decision makers. Moreover, the Arctic's natural resources are ultimately more significant in political terms than because of their commercial attractions. The governments of several arctic rim states also acknowledge an obligation to protect the welfare of indigenous peoples, as well as a broad public interest in safeguarding the Far North's principal ecosystems. Thus, the future of the Arctic will be shaped far more by public policies than by the free play of market forces or other private-sector considerations. Additionally, international cooperation in handling environmental issues and managing increasingly complex transportation systems must be important arctic policy priorities.

Second, both the Soviet Union and the United States badly need a group of more broadly trained arctic experts. The Soviet Union has long been recognized as a world leader in arctic science, especially in atmospheric sciences, physical oceanography, glaciology, and arctic engineering. Moscow's leading agency is the Arctic and Antarctic Scientific Research Institute. Overall, more than 20,000 Soviet scientists are thought to engage in some form of arctic research. In 1984, the Soviet Union and Canada agreed to promote arctic scientific cooperation and exchanges. There is, unfortunately, no comparable U.S.-Soviet agreement, though cooperation sometimes occurs on specific projects.

The Arctic's natural resources are ultimately more significant in political terms than because of their commercial attractions.

The American effort to foster arctic scientific research is more fragmented but nonetheless substantial. Despite a definite bias toward the Antarctic, both the Division of Polar Programs of the National Science Foundation (NSF) and the Polar Research Board of the National Academy of Sciences regularly sponsor arctic research in the physical sciences. The Arctic Science Program of the Pentagon's Office of Naval Research funds arctic research of potential interest to military planners. The Outer Continental Shelf Environmental Assessment Program, administered by the National Oceanic and Atmospheric Administration, and Congress's Office of Technology Assessment are researching hydrocarbon development in the Arctic. These governmental initiatives have also resulted in the establishment of several university-based centers to conduct arctic research in the natural sciences—notably, the Geophysical Institute at the University of Alaska at Fairbanks, the Institute of Arctic and Alpine Research at the University of Colorado, and the Institute of Polar Studies at Ohio State University.

The Arctic Research and Policy Act of 1984 established two new federal entities to coordinate arctic research: the five-member Arctic Research Commission (ARC), composed of private citizens appointed by the president, and the Interagency Arctic Research Policy Committee, chaired by the NSF representative. Despite some promising initiatives, it remains to be seen whether these changes will greatly improve U.S. performance in arctic science.

At the same time, Moscow and Washington have done nothing to address their growing need for more broadly based arctic experts. The United States, for example, has no established program suitable for those desiring a systematic

The federal government and the State of Alaska have repeatedly found themselves on opposite sides of litigation over offshore oil and gas development and wildlife management in the Arctic.

understanding of arctic issues. The Division of Polar Programs funds no research at all on arctic military, political, and socioeconomic developments. No more than a handful of American scholars take an active interest in the political economy of arctic Alaska or in Greenland's politics. And practically no one closely follows major events in the Soviet Arctic.

The absence of a group of Soviet experts in these fields may well stem from general ideological limitations on the work of Soviet social scientists. Moreover, social research on the Soviet North would probably bring out embarrassing information regarding the treatment of political exiles and the administration of indigenous peoples. The lack of American arctic expertise probably results from the widespread tendency to dismiss the region as a remote, unimportant wasteland. But this view is now dangerously outdated.

Major policymaking improvements are required as well. The Soviet Union, for example, clearly has problems handling arctic affairs in a coordinated fashion, as indicated by the engineering failures afflicting construction of the Siberian gas pipeline and the near loss of dozens of ships to the Arctic ice during late summer and fall 1983.

Recent U.S. Initiatives

Room for improvement exists in Washington, too. The basic mechanism for handling arctic policy issues in the United States is the Interagency Arctic Policy Group (IAPG), established under the provisions of National Security Decision Memorandum 144 of 1971 and reaffirmed under the terms of National Security Decision Directive 90 of 1983. The IAPG is responsible for developing and overseeing the implementation of American arctic policy as well as for coordinating American arctic activities and programs. Chaired by a representative of the Department of State (usually the assistant secretary for Oceans and International Environmental and Scientific Affairs), the group includes representatives from a number of agencies but ultimately reports to the National Security Council in the Executive Office of the President.

Unfortunately, this mechanism has severe limitations as an arrangement for handling arctic policy issues. The IAPG has experienced frequent periods of dormancy (it seldom met during the Ford and Carter Administrations), failing to meet even when major arctic policy issues have surfaced. More often than not, the group has become active only when its members have perceived some threat to their turf, such as the newly created Arctic Research Commission. Member agencies whose concerns are primarily domestic are suspicious of the role of the State Department as lead agency in the IAPG and are reluctant to accept the group as an authoritative forum for reconciling arctic conflicts.

To illustrate, the Department of the Interior and the Commerce Department do not accept the comparatively conciliatory views of the State Department regarding issues like jurisdiction over the Navarin Basin in the central Bering Sea and the regulation of foreign fishing vessels throughout the Bering Sea. The IAPG also has failed to establish any effective procedure for coordinating federal and state concerns regarding arctic issues. As a result, the federal government and the State of Alaska have repeatedly found themselves on opposite sides of litigation over offshore oil and gas development and wildlife management in the Arctic.

Even less effort has gone into devising a suitable method for integrating the legitimate concerns of the native peoples of the Arctic into the policymaking process. The result is that native organizations and the federal government confront each other in court again and again in cases relating

There are no established procedures for regular, high-level consultations between the United States and its northern allies or neighbors regarding newly emerging arctic issues.

to the socioeconomic impacts of oil and gas development, the use of arctic animals for subsistence purposes, and native claims to marine areas in the Arctic, despite the acknowledged obligation of the federal government to protect the welfare of native peoples.

Additionally, there are no established procedures for regular, high-level consultations between the United States and its northern allies or neighbors regarding newly emerging arctic issues.

Adding to all these problems is the fact that little has been done to provide the IAPG with a sophisticated conception of the Arctic as a well-defined and distinctive region of the world. Consequently, American policymaking for the Arctic

A Soviet arctic research station. (Photo courtesy of Novosti)

does not flow from any profound understanding of the interactions among the physical, biological, and human systems of the region.

It is not surprising, therefore, that Congress often ignores the existence of the IAPG in its dealings with the Arctic. The Arctic Research and Policy Act of 1984, which purports to establish a comprehensive policy dealing with national research needs and objectives in the Arctic, makes no reference to the IAPG. As a result, the relationship between the Arctic Research Commission and the IAPG is unclear, and friction between the two organizations has already emerged. Understandable though this may be, it is hardly a sign of the existence of an effective policymaking apparatus for arctic issues.

It is tempting to look to the Arctic Research and Policy Act for a new approach to arctic policymaking. Whatever its role in providing a stimulus for arctic science, however, the act has little to offer as a basis for formulating arctic policy more generally. The principles it sets forth pertain only to arctic *research* policy, and the organizations it establishes (that is, the Arctic Research Commission and the Interagency Arctic Research Policy Committee) have mandates extending only to arctic science. The provisions of the act do nothing to replace or even to limit the authority of the IAPG. As the preceding discussion suggests, moreover, the act fails to address the problem of coordinating the work of the Commission and the Research Policy Committee with the activities of the IAPG, an entity which retains its original mandate to oversee American arctic activities and programs. What this suggests is the need for a high-level Council on Arctic Policy created by an act of Congress, located in the Executive Office of the President, and chaired by a distinguished person appointed specially to fill this role. It is time for U.S. arctic policy to come out of the deep freeze.

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Glaciology—A Primer On Ice

by Norbert Untersteiner

A quick glance at a satellite photo of the Arctic Ocean reveals its most distinguishing feature—ice. In the central Arctic, ice forming on open water in the fall may be 2 meters thick by the following spring, and may not melt during the summer. Sea ice is a composite of pure ice, brine pockets, and gas bubbles. Varying in extent seasonally, this ice cover affects arctic climate, ocean circulation, and marine biology, and also impacts virtually every human use of the region. Understanding the properties of this unique ocean surface is therefore of utmost importance.

Ice Formation and Physics

When sea ice begins to form, it is a loosely bound mixture of small plates and spine-like crystals; this stage is called frazil ice. Each crystal is virtually pure ice, as the crystal structure accommodates very few atoms other than hydrogen and oxygen. Thus, as seawater freezes, the dissolved solids are excluded from the ice crystals and enrich the concentration of the remaining brine. As the frazil ice becomes more densely packed, some brine is trapped within the ice. If freezing continues, the advancing bottom surface of the ice attains a deeply corrugated pattern. Occasionally these corrugations are closed off by ice crystals, thus trapping small pockets of brine within the ice. Gases dissolved in the seawater (roughly equivalent to air in composition) are also excluded from the ice crystals, and form bubbles within the ice.

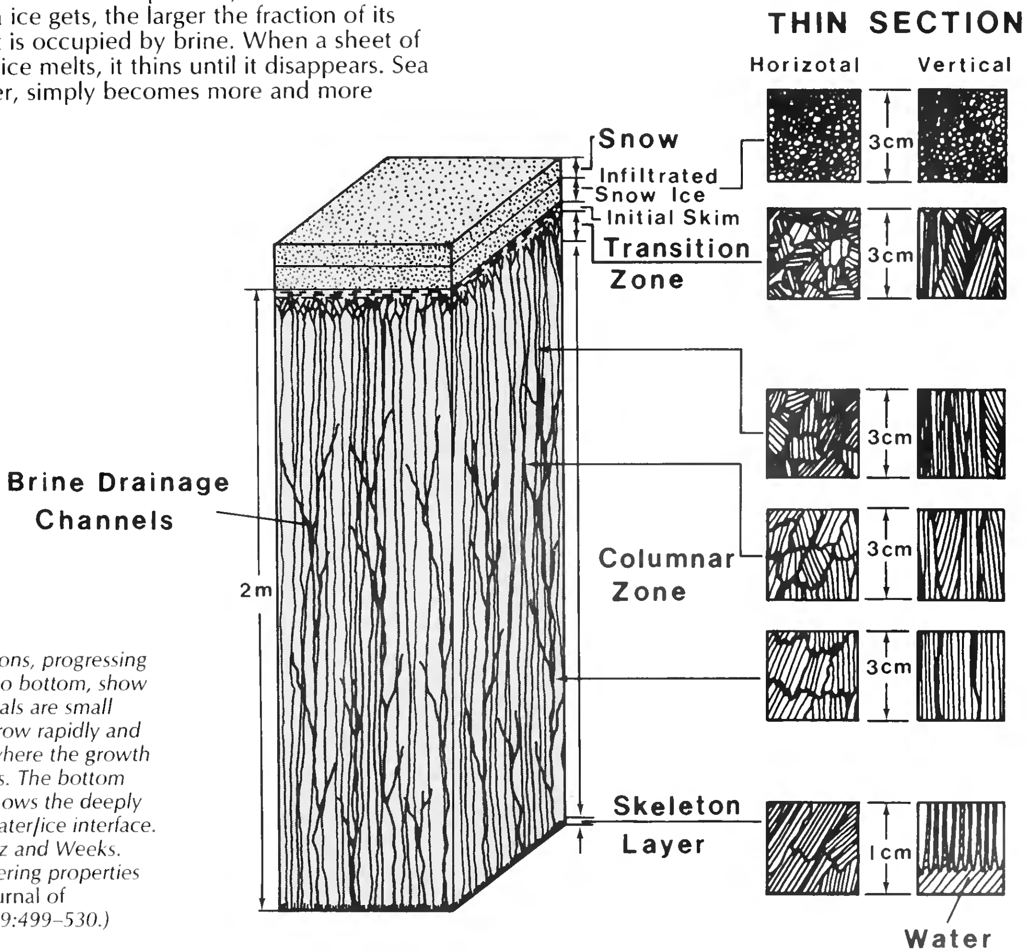
Many of the fascinating and peculiar properties of sea ice depend on this composite structure. For example, thermodynamic principles

In picture above, new thin ice is growing where two old ice floes have separated. (Photo courtesy of author) dictate that the freezing point of salty water decreases as the salt concentration increases. This principle is employed by public works departments across the country each time it snows. In normal seawater, salt concentrations are about 35 parts per thousand, and the freezing point of the mixture is −1.9 degrees Celsius.

Thermodynamics also dictates that at any given ambient temperature, brine must be at its freezing point when in contact with ice. For brine pockets trapped within sea ice, this means that either additional freezing or melting will occur as temperatures change. For example, if the temperature drops, ice forms on the walls of the brine pockets, making them smaller and increasing the concentration of the enclosed brine. If the temperature rises, the salty brine will begin to dissolve the surrounding ice, thus diluting itself. The amount of heat added, or taken from, a volume of sea ice when it changes temperature consists of two parts: one to change the actual temperature of ice and brine, and the other to accomplish the change-of-phase (freezing or thawing) within the brine pockets. Per unit volume, the latter is about 150 times greater than the former.

Thus, the warming of sea ice is accompanied by an expansion of brine pockets; the warmer a piece of sea ice gets, the larger the fraction of its volume that is occupied by brine. When a sheet of fresh water ice melts, it thins until it disappears. Sea ice, however, simply becomes more and more

Frazil ice, showing spine-like crystals. (From Weeks and Ackley, 1982. The growth, structure, and properties of sea ice. CREEL Monograph No. 82-1)



The thin sections, progressing from surface to bottom, show how the crystals are small where they grow rapidly and grow larger where the growth rate decreases. The bottom right frame shows the deeply corrugated water/ice interface. (After Schwarz and Weeks. 1977. Engineering properties of sea ice. Journal of Glaciology. 19:499–530.)

Two converging ice floes have crumbled at their edges and have formed a pressure ridge about 1 to 4 meters high. An ice camp is visible in the background. (Photo courtesy of the author)

porous, until it disintegrates into a mass of individual ice crystals.

This interaction between brine pockets and ice crystals has many implications:

- *A thick layer of sea ice will disintegrate first at the surface, where heating is most intense. The resulting loose, granular surface layer has many reflecting surfaces, which reflect more sunlight than would a solid layer of ice. This retards the melting of the rest of the ice.*
- *When sea ice becomes porous enough that brine pockets become interconnected (as may happen each summer), the nearly pure water generated by melting of ice crystals at the surface will tend to flush the brine from deeper layers. This mechanism probably accounts for the observation that the older the ice, the lower the salinity.*
- *When a sheet of sea ice is warm and a large fraction of its volume is brine, it will take longer to cool than a comparable sheet of fresh water ice, because of the large amount of heat given off as the brine pockets cool and refreeze. This heat must be released to the surrounding environment—for instance, by infrared radiation loss at the surface—before rapid cooling of the whole ice sheet can occur.*
- *The variation in the volume of brine within sea ice affects the thermal conductivity of the ice, its strength and other mechanical properties, and its radiative properties—important for remote sensing efforts. The radiative properties will affect the radiation received by a sensor in space or on an aircraft, and hence must be considered in interpreting such remote sensing data in terms of the physical condition of the ice (temperature, thickness, roughness, etc.).*

Unlike the brine pockets, the gas bubbles in the ice do not change much over time or with variations in temperature. They do, however, act as internal reflecting surfaces, and as such affect the way in which the ice scatters and absorbs radiation.

Growth, Melting, and Regrowth

On open water in the central Arctic, ice begins to form at the end of summer (early September). By the following spring the ice cover may be two meters thick. About 30 to 40 centimeters of snow will fall on top of the ice during the autumn, until the air becomes so cold that it cannot carry significant amounts of moisture and precipitation nearly ceases. As temperatures rise during May and June, another 5 to 10 centimeters of snow fall.

Melting commences in late May or early June, and will typically remove the entire snow cover and an average of 40 centimeters of ice. After the snow has melted, many shallow ponds form on the surface of the ice sheet. As the summer progresses they become smaller and deeper. The ponds reflect less solar radiation than the surrounding ice, and so tend to become "windows" for heating the ice and even the seawater beneath it.

In mid-September, freeze-up begins. As the ice cools, the ponds solidify, and when the entire ice sheet has solidified, new ice begins to accrete onto the bottom of the sheet. Under today's climatic conditions, more ice forms during the second winter than was removed by melting and evaporation during the previous summer. Hence, the ice sheet tends to thicken. This thickening progresses most rapidly during the first years of the ice sheet's existence, and tapers off later, because of another phenomenon: as the ice thickens, it takes longer to cool in the fall, and hence ice accretion begins later and progresses more slowly during the fall and winter.

Thus the ice sheet approaches an equilibrium thickness, at which summer melting equals winter accretion. Except for cyclical seasonal changes, the ice has reached a steady state, with the oldest ice at the surface, new ice forming at the bottom, and a flux of ice in the upward direction because the oldest ice melts off each summer.

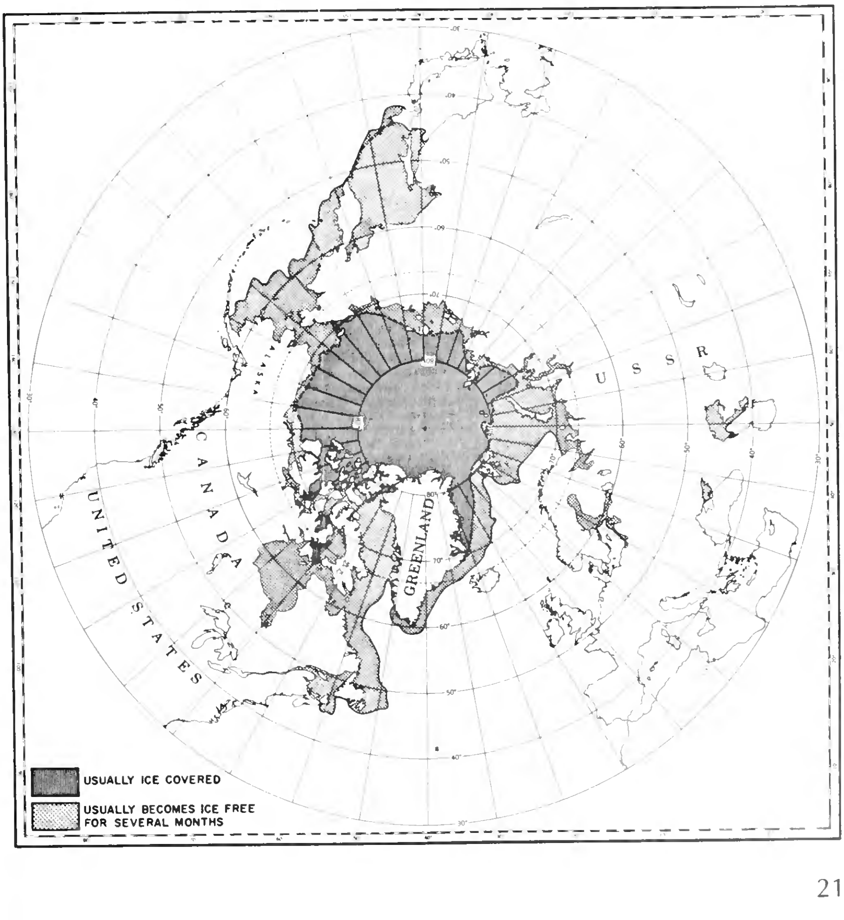
The equilibrium thickness is controlled by the exchange of heat between atmosphere, ice, and ocean. In the Arctic Basin, this equilibrium thickness is between 3 and 4 meters. The physics of this interaction is well understood, and can be simulated by thermodynamic models. Such models also are of some use in extrapolating growth and melt rates that may have prevailed under different climatic conditions.

Unfortunately, the picture just presented is like a black-and-white snapshot of a colorful scene—part of the true situation is missing: except in protected bays and fjords, the undisturbed growth of ice described previously never occurs. Winds and currents crack, break up, warp, and otherwise disturb the ice; and even small changes in climatic conditions can drastically alter the distribution of the ice in arctic regions.

Ice Distribution

Sea ice is but a thin skin of frozen water covering the polar oceans. Being thin, it represents a minute fraction of the total amount of heat gained and lost by the Earth's surface in the course of a year; consequently, it is not surprising that the presence or absence of sea ice can be brought about by very small changes in the global heat exchange. In this context, it is useful to recall that the arctic sea ice cover at its maximum extent has an area 40 times greater than that of all the mountain glaciers in the world (excluding the ice sheets of Antarctica and Greenland), but its volume is five times smaller. This large surface-to-volume ratio results in a rapid response to climatic changes (see page 41).

The distribution of land and ocean in the Arctic controls sea ice distribution. At the end of summer (August) the sea ice cover recedes to the Arctic Basin proper, leaving wide bands either of open water or of water with low ice concentration along the coasts of Eurasia and Alaska. At the time of maximum extent in March, the ice nearly doubles its extent and covers all the arctic marginal seas (15 million square kilometers or 10 percent of the Northern Hemisphere's ocean surface). Especially in the Atlantic sector, the distribution shows a strong zonal asymmetry. To the east, the ice is restricted to the Barents Sea at about 75 degrees North by the warm waters of the Gulf Stream, while in the west, ice regularly appears in the Gulf of St. Lawrence at 45 degrees North, a



Map at right depicts the extent of the Arctic ice cover.

latitude corresponding to that of Venice and the swimming beaches of the northern Adriatic.

The tongue of sea ice reaching south into the Greenland Sea is a prominent feature throughout the year. Only about half that ice is of local origin. The other half is carried into the Greenland Sea by the East Greenland Current. This ice constitutes a large fraction of the seasonal ice production of the Arctic Basin; the exact fraction, however, is not known.

Ice Movement

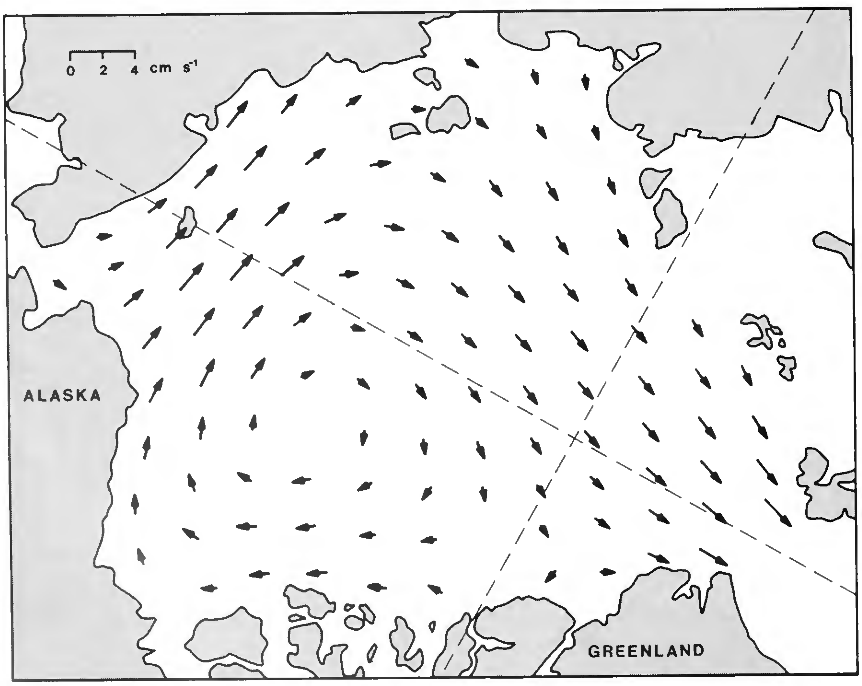
Even in the central Arctic, sea ice is always moving, driven by winds and ocean currents. These two phenomena take place in the continuous and well-mixed media of the atmosphere and ocean, and hence variations in their characteristics may take place on scales of hundreds or thousands of kilometers; even oceanic or atmospheric "fronts" typically measure kilometers across. Sea ice, however, is not a continuum, but an ensemble of rigid pieces that crack, shift, and ridge, or raft, in discrete, localized events. Thus, forces acting over hundreds or thousands of kilometers produce ice effects on scales measured in meters. The crucial mechanical failures may take place on an even smaller scale.

By geophysical standards, a large body of knowledge exists about the characteristics of sea ice as a function of temperature, salinity, and crystallographic structure. This knowledge is regularly used in such engineering endeavors as calculating the ice resistance encountered by ships or designing oil drilling platforms for ice-covered waters. But no method has yet been found to relate this knowledge of the large-scale response of an ensemble of sea ice pieces to small-scale ice mechanics.

Such difficulties have not deterred scientists from devising theories of ice dynamics; these have involved some law that relates stress and strain in ice and so can describe the cumulative effect of a multitude of small-scale events caused by large-scale phenomena (such as winds and currents). Thus, the ice has been described as isotropic viscous, anisotropic viscous, incompressible, plastic, elastic-plastic, and viscous-plastic. Some models based on one of these various assumptions have met with considerable success; meaning that, to the limited extent that we know the forces affecting sea ice, an ice velocity field can be computed that bears strong resemblance to the observed one (see diagram below). But finding an ice rheology that "works" is not synonymous with understanding it; the mechanics involved in ice deformation remain a challenging and difficult problem.

The Marginal Ice Zone

Nowhere are ice dynamics more complex than in the marginal ice zone (MIZ) (see page 66). This region extends from the ice/open water boundary about 100 kilometers into the ice and 100 kilometers out over the ocean. In most areas, the MIZ moves seasonally, in the extreme case by more than 2,000 kilometers; in other areas, it is essentially stationary. But everywhere the zone is characterized by a complex and rapidly changing interplay between atmosphere, ice, and ocean on a multitude of temporal and spatial scales. Important MIZ phenomena include ocean fronts and eddies, rapid local changes of the surface roughness of both ice and ocean (and therefore of wind and water stress on the ice), vertical movement in the ocean, local winds and atmospheric circulation



Average ice drift velocity in the Arctic Basin, as observed during several years by automatic buoys. The long-term average ice drift is 1 to 2 kilometers a day. On any given single day, the ice travels typically 6 to 8 kilometers. (From Colony and Thorndike, 1984)

Table 1. Automated observations of sea-ice conditions by satellites and data buoys.

Parameter	Current Frequency of Observation	Status
Ice extent	Daily	Reliable
Ice concentration	Daily	Some problems with satellite image interpretation remain
Ice drift	Several times daily	Reliable
Geostrophic wind	Daily, several times daily possible	Reliable
Air temperature	Several times daily	Reliable, except in summer
Ice temperature	Daily	Reliable, but few applications yet
Ice thickness	Experimental	Potentially reliable
Ocean mixed-layer temperature	Daily	Reliable, but few applications yet
Ocean mixed-layer salinity	Experimental	Sensors need improvement
Vertical flux of heat	Experimental	Under development

patterns caused by strong surface temperature gradients, deep ocean convection caused by sea ice formation, differential ice drift depending on floe size, and ice break-up by waves and swells from the open ocean.

Because of this complex interaction between ice, atmosphere, and ocean, the MIZ is extremely sensitive to small changes in temperature, winds, and other climatic phenomena. While there is no question that trends of climatic change must have produced changes in the ice cover of the Arctic Basin, such changes have not been conclusively documented. But large and systematic changes have been recorded in the MIZ, expecially in the Greenland Sea. Partially, such changes are well-documented because the MIZ has long been of commercial maritime interest, but even more importantly, the MIZ is more sensitive than other sea ice regions to climatic change. There is little doubt that understanding air/sea/ice interaction in the marginal ice zone will be the key to understanding the interplay between global climate and sea ice.

Keeping Watch Over Ice

Further understanding of sea-ice dynamics will depend on improved observations of the ice. Most of our present knowledge about the properties of sea ice and its interactions with the atmosphere and ocean is derived from observations taken from ships and drifting ice stations. While these have been extremely useful, they lack the synoptic view over large areas necessary for understanding both the large-scale interplay between the atmosphere and ocean in high latitudes, and the behavior of sea ice as the intervening medium.

Since the early 1970s, satellites have routinely provided pictures of global sea ice cover (see page 59). This breakthrough was followed by the successful use of automatic data buoys, a technology that grew out of and depended on the development of satellite navigation and data transmission devices, and microelectronic techniques for storing, preprocessing, and transmitting the data obtained by on-site sensors. Thus more and more data is being gathered by automatic sensors in the Arctic and satellites in space. Ships and ice camps are still required for many kinds of specialized observations, but during the last decade the acquisition of the basic data has become roughly an order of magnitude less costly, and roughly an order of magnitude more data are now being collected. The most important data and the state of the art in their collection are shown in Table 1.

These observations, combined with information from specialized research projects will increase our understanding of arctic sea ice—an understanding vital to a multitude of national concerns about the Arctic.

Norbert Untersteiner is Professor of Atmospheric Sciences and Geophysics at the University of Washington, and also Scientific Director of the Polar Science Center there.

Suggested Readings

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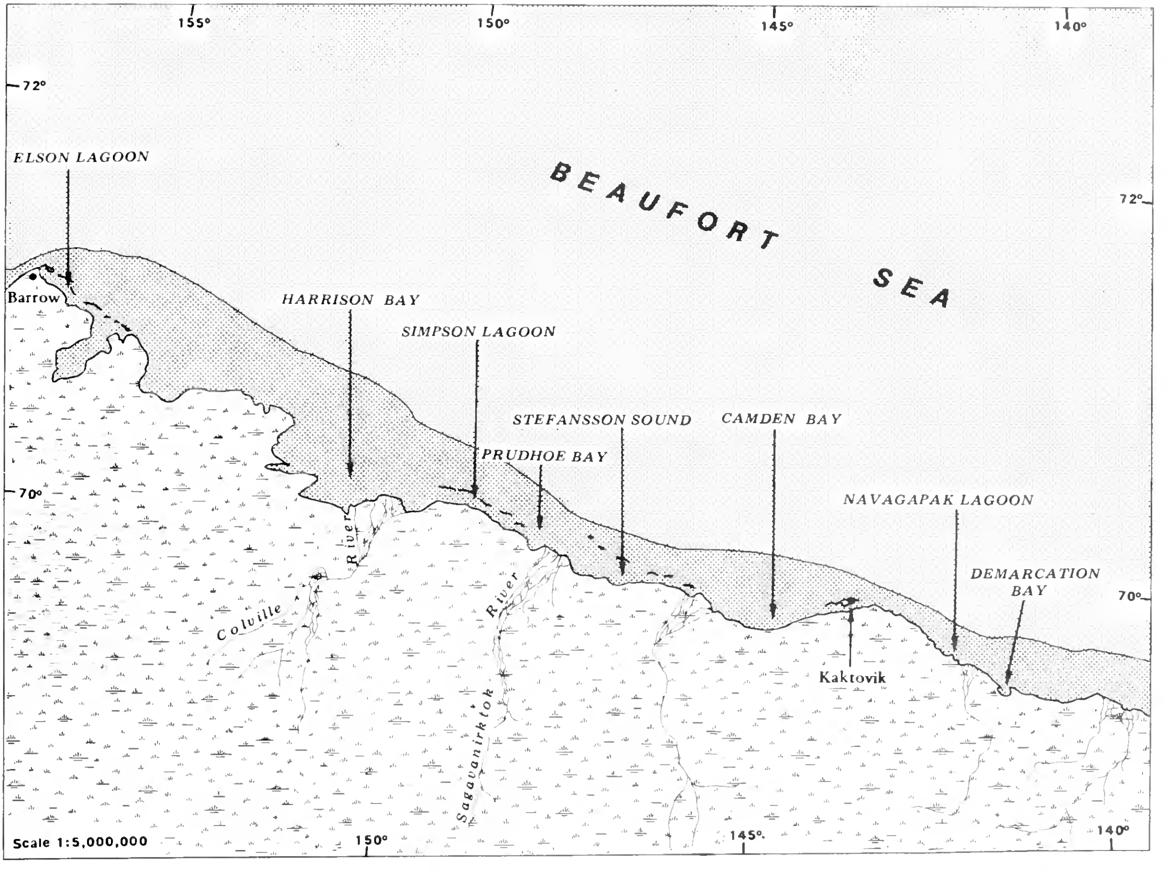
Sea Ice and Oceanographic Conditions

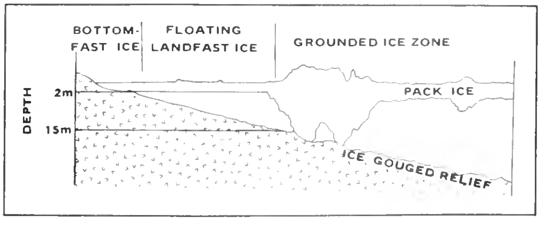
by Thomas Newbury

The coastal waters of the Beaufort Sea are locked under ice for three-fourths of the year. Historically, only Alaskan natives, whalers, and occasional explorers ventured out onto the surface of the ice or found much of value in the chilling waters beneath; and so these waters remained unknown, at least in winter. During the last three decades, the Naval

Tubular stalactites hanging from the under surface of the landfast ice in the Beaufort Sea—among the many unusual features of the Arctic's under ice areas. (Photo by Bob Britch, Northern Technical Services, Inc.)



Above, landfast ice (slightly darker shading) along the Alaskan portion of the Beaufort Sea coast. Right, bottomfast ice is found in less than 2 meters of water, floating landfast ice in 2 to 15 meters of water, and grounded and mobile pack ice in deeper water. (Right-hand diagram adapted from U.S. Army Cold Regions Research and Engineering Laboratory)



Petroleum Reserve in Alaska* was explored, oil was discovered near Prudhoe Bay, and then exploration began in earnest offshore in the U.S. and Canadian portions of the Beaufort Sea. The coast of the Beaufort Sea rapidly became the focus of international research, and the need for continued research prompted the recent passage of the Arctic Research and Policy Act (see page 2). Private industries and government agencies have begun exploratory research on this unknown marine realm, attempting to understand the severe conditions that continually challenge those involved in year-round oil exploration and extraction.

Oceanographers have begun to examine the coastal waters of the Beaufort Sea during winter. The research has focused on the shallow bays and coastal lagoons where oil drilling appears to be most practicable.

* A large area on the Alaskan North Slope originally set aside to provide petroleum for Navy operations in the event of war.

Consolidation of Coastal Ice

Freeze-up initiates the changes that each fall turn the coastal waters of the Beaufort Sea from a typical (albeit cold) marine environment to a realm of unique phenomena. Freeze-up begins when the dense, broken layer of ice that forms in the fall starts to solidify, and can take several months. The exact timing of freeze-up is difficult to predict. Don Ljungblad of the Naval Ocean Systems Center, who has flown almost daily along the Alaskan coast observing the fall bowhead whale migration through the area, reports that the ice cover generally solidifies by mid-October, but sometimes solidifies as early as September. Some years it may remain broken until December. The timing of freeze-up has dramatic effects on industrial operations and may have large climatic effects as well. Formation of an unbroken ice sheet signals that winter has consolidated its hold.

During freeze-up, a long thin band of ice begins to fringe the Beaufort Sea, adhering to the frozen shore. Along the 600-kilometer Alaskan border of the Beaufort, the "landfast" ice ranges in width from only 15 kilometers near Barrow and Kaktovik to 60 kilometers near Harrison Bay. The zone of landfast ice is wedged between the shore and the multi-year pack ice that forms a permanent, rotating mantle on the outer Beaufort Sea and Arctic Ocean. On the outer edge of the landfast ice—generally in 15–20 meters of water—huge chunks of ice are upended and jammed against the sea bottom by movements of the pack ice. This grounded ice zone, or stamukhi zone, stabilizes and protects the outer edge of the relatively thin, flat landfast ice from grinding by the pack ice. Adjacent to shore, landfast ice freezes solid from the surface to the bottom. This "bottomfast" landfast ice marks the inner edge of the zone of floating landfast ice. Underneath the floating landfast ice is a long ribbon of water, more or less isolated from the waters under the pack ice.

A Ribbon of Under-Ice Water

The water under the landfast ice undergoes a variety of changes during freeze-up. To begin with, water trapped beneath the landfast ice grows gradually more saline. Dissolved salts are excluded from the seawater during the freezing process (see page 18) and become increasingly concentrated in the underlying unfrozen seawater. In Stefansson Sound, for example, salinity was at 32 parts per thousand in November (equivalent to the salinity of open water in the Beaufort Sea) and had a freezing point of −1.7 degrees Celsius, as calculated by Brian Matthews from the University of Alaska; by December, when another 30 centimeters of ice had formed, the salinity had risen to 33.2 parts per thousand and the freezing point had dropped to −1.85 degrees Celsius.

Changes in under-ice salinities and temperature during freeze-up lead to two particularly interesting phenomena: development of frazil ice and formation of stalactites. The frigid temperatures of the under-ice water cause ice crystals to form on objects in the water column; these crystals are known as frazil ice. On several occasions, ice crystals that had formed on current meter blades stopped the meters; once, ice crystals on a current meter tripod created sufficient buoyancy to lift the tripod 2 meters off the seafloor and tip it over. Ice crystals accumulating on particles of sediment on the ocean floor provide a mechanism by which the particles may float up and become incorporated into the overriding ice cover.

Stalactites form where very cold dense brines, excluded during freezing, drain downward from the undersurface of the ice sheet. These brines may have salinities of 65 parts per thousand and freezing points of −4 degrees Celsius. As they drain downward, into seawater that is very near its freezing point, the surrounding molecules of seawater are cooled and freeze together to form hanging tubular stalactites. The stalactites may grow to 25 centimeters in diameter and several meters in length. They commonly form under ice that froze rapidly the previous fall, incorporating some brine. During the long winter, the ice slowly releases the trapped brines, allowing the stalactites to form.

Brine Circulation

Circulation patterns in the waters beneath the landfast ice change dramatically during and after freeze-up. With formation of an extensive ice cover in the fall, coastal waters are insulated from wind, the main driving force of coastal circulation during summer. As a result, current velocities under the ice decline from summer velocities of 10 centimeters a second to mean velocities of a tenth of a centimeter per second in January.

With the effects of wind removed, other forces control the circulation patterns underneath the landfast ice. Occasionally, for example, the water under the ice surges along the coast in either direction at speeds of 4 centimeters per second. These surges may be related to tides, which in the Beaufort Sea are controlled primarily by climatological and meteorological forces rather than by the more familiar gravitational pull of the moon and sun. Meteorological tides caused by local, low pressure storms can have 10 times the force of regular "lunar" tides; changes in air pressure over the ice probably account for surges of water trapped underneath the landfast ice cover.

Variations in salinity also affect under-ice circulation. Highly saline brine draining from ice as it freezes is denser than surrounding seawater. As a result, brine sinks to the seafloor and then flows down the slope of the continental shelf into offshore areas. Knut Aagaard at the University of Washington has found traces of this cold saline water across the continental shelf and down to the subsurface halocline layer in the Arctic Ocean. A complementary onshore flow of relatively light seawater may occur just below the ice.

In the middle of Stefansson Sound, the offshore flow of hypersaline brine continues until late winter when freezing slows, cutting the flow of brine to a point where it no longer moves bottom drifters used to detect seafloor movements of water.

Where the offshore drainage of brines is restricted, as in topographic depressions or behind underwater barriers, local salinities may eventually rise to very high levels. Salinities rose to 70 parts per thousand in a small basin within Prudhoe Bay and to 182 parts per thousand behind a gravel bar in Elson Lagoon. Development of high local salinities suggests that natural drainage of seawater is very poor in some areas, and hence, that dispersion of water-borne contaminants from these relatively stagnant areas would be very slow, a condition that causes concern among some biologists interested in the organisms living in these areas.

Nutrient Regeneration in Calmed Waters

Circulation patterns naturally have important effects on the movements of nutrients. The onshore-offshore water movements described previously are believed to transport phosphate-rich offshore waters into phosphate-deficient coastal areas. Two other mid-winter factors also raise nutrient levels in under-ice waters: the freeze-induced concentration of solutes (including nutrients and gases) in the underlying water, and regeneration of nutrients by microbial activity. These processes lead to a rise in the concentration of nitrogen in the form of nitrate and nitrite from less than 0.1 micrograms per liter in early November to about twice that concentration by the end of the next four, dark months.

Like other physical factors, the turbidity of offshore waters changes dramatically during and after freeze-up. Fall storms sometimes mix large amounts of sediments into the water, so coastal waters often are very turbid during freeze-up. Peter Barnes of the U.S. Geological Survey, and Thomas Osterkamp and Joan Gosink at the University of Alaska have hypothesized that rapidly freezing ice may incorporate much of the suspended sediments.

After freeze-up, ice protects the underlying water from storms. Sediments gradually settle out of the calmed waters. Occasional turbid layers of water are observed, probably caused by storm-induced water surges, or possibly by ice crystals resuspending particles of sediment. By mid-winter, light transmissivity through these cleared waters, however, equals that of air.

Biological Energy

Despite the dramatic changes in salinity, temperatures, circulation, turbidity, and nutrients, biological activity continues under landfast ice throughout fall and winter. But another physical factor has an overriding effect on the activity of organisms under the ice cover: the darkness of winter. For three months, there is no direct sunlight, and for five months, from November until March, chlorophyll is barely detectable in phytoplankton. With the cessation of photosynthesis, and hence primary food production, other sources of biological energy increase in importance. Animals living under the landfast ice rely on three sources of energy: fat, other organisms, and detritus.

Fat is stored by many animals during the summer months. Such reservoirs of energy include the familiar layers of blubber developed by seals and whales, as well as the energy-rich fat globules within the bodies of arctic invertebrates.

Another, temporary source of winter food is under-ice organisms—populations of which are generally at annual highs as winter begins, having grown rapidly during summer and early fall. As a result, animal foods are relatively abundant, and—since they have been storing fat—especially rich, during at least the beginning of winter.

The third source of food that sustains organisms through the long dark winters is dead organic matter, or detritus. Much detritus is available in nearshore areas, primarily from the discharge of rivers and from the erosion of coastal peat banks. In fact, Don Schell's research at the University of Alaska shows that more than half the total yearly input of organic carbon to nearshore areas may come from detritus. The importance of organic carbon derived from peat led Schell to describe this as an ecosystem with a "fossil fuel subsidy." Much of the detritus is added to coastal waters during fall storms. As winter locks up the rivers and ocean surface with ice, coastal erosion ceases, and the winter's supply of land-derived detritus is limited to what has been sealed into the ice-covered waters.

Life Under Ice

The variety of organisms managing to overwinter on these limited sources of energy is surprisingly diverse. Bacteria are the simplest of these, and constitute the main consumers of detritus. The enzymes present in bacteria indicate a seasonal shift to detrital food resources during winter, and bacterial activity is greatest where concentrations of detritus are greatest, namely in sediments near coastlines and especially near river deltas. Even in these relatively rich areas, however, bacterial

A shrimp-like amphipod grazing among the loose ice crystals on the bottom surface of the ice. This area is crucial to the under-ice ecosystem in spring. The amphipod is about 3 centimeters long. (Photo by Ken Dunton, University of Alaska)

Kelp beds are found in few areas under the ice, but where found they support a unique under-ice community. A small sponge is visible among the kelp at upper center. (Photo by Ken Dunton, University of Alaska)

metabolic activity drops during winter; activity in January may be only a tenth of the high levels of activity measured in August.

The epibenthic invertebrates also depend partially on detritus. Among the epibenthic invertebrates found under floating landfast ice are numerous small, shrimp-like crustaceans, including several types of amphipods (for example, *Gammarus setosa*, and *Onisimus litoralis*), the mysid *Mysis litoralis*, and the isopod *Saduria entomon*. However, most of the detrital carbon epibenthic invertebrates assimilate comes to them indirectly through their consumption of bacteria, which is partly why carbon from dead organic matter is transferred very inefficiently through the food web.

Two adaptations allow these epibenthic invertebrates to survive the harsh winter conditions beneath the coastal ice. To begin with, these creatures are mobile. As a result, they can escape being frozen into the thickening ice cover in shallow areas where it reaches the ocean floor. They also can avoid the ice keels that commonly gouge a meter into the seafloor in the stamukhi zone. In addition, these invertebrates can tolerate wide ranges in both salinities and temperatures.

Another group of organisms that consumes some detritus is the benthic infauna.* Although the biomass of these organisms appears to be roughly equal to the biomass of epibenthic invertebrates, their overall contribution to the under-ice food web is apparently lower than that of the epibenthic invertebrates because fewer organisms consume infauna. In addition, seafloor disturbances, such as gouging ice keels and pools of cold brine, may reduce the productivity of the infauna; this may, in part, explain their relative unimportance in the under-ice food web.

Kelp and Larger Animals

One special group of benthic organisms deserves mention. Kelp live in a few isolated areas under the landfast ice with associated assemblages of organisms on the otherwise featureless seafloor of muddy sand. The largest and densest kelp community in the Alaskan Beaufort Sea is distributed over several square kilometers in Stefansson Sound. Other kelp communities are in Camden Bay, Navagapak Lagoon, and Demarcation Bay.

Kelp is not photosynthetically active during winter; activity appears to be limited to tissue translocation along the 2-meter fronds. But animals associated with the kelp do remain active. During under-ice dives, polyps of the soft coral *Gersemia rubiformis* were usually seen in open feeding position. Also, a rare snailfish, *Liparis spp.*, was always observed near or resting on kelp fronds.

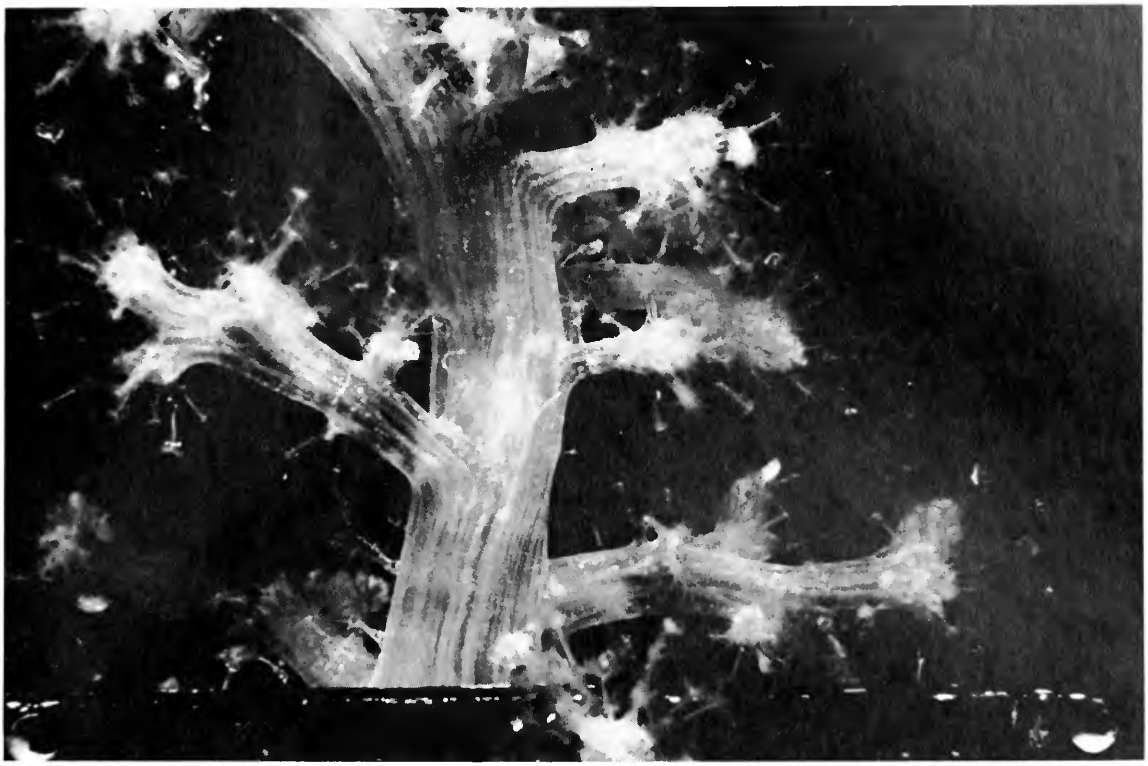
The distribution of the kelp communities is restricted by several factors. As mentioned already, in shallow areas ice freezes to the ocean bottom, precluding the survival of attached organisms. In areas deeper than 15 meters, upended pieces of ice regularly scour the bottom. In nearshore areas around deltas, sediments carried to the sea by rivers bury attached organisms, as do sediments from rapidly eroding shorelines. Finally, few areas provide a solid substrate to which sessile organisms like kelp can attach. Kelp in Stefansson Sound, for example, are attached to pebbles from an old, eroded glacial deposit.

The upper levels of the under-ice food web are occupied by fishes and seals. Fishes primarily consume the epibenthic fauna. Both fishes and invertebrates, in turn, provide food for ringed seals (*Phoca hispida*, or Natchiq to Alaskan natives). In these upper trophic levels, the organisms feed and reproduce actively during the long winter.

A Seasonal Nadir

Activity in the under-ice food web slows down, in general, by late winter. The under-ice food supply and metabolic activity appear to reach a "nadir." As mentioned earlier, bacterial activity in January is 10 times slower than in August. Gut fullness observed in epibenthic invertebrates and fishes decreases steadily through fall and into early spring, and the

* Organisms living on or in soft sediments, such as mud.



An under-ice coral, showing the polyps in open feeding position. (Photo by Ken Dunton, University of Alaska)

overall biomass of the epibenthic invertebrates decreases similarly. By April, when under-ice photosynthesis has resumed, measurements of microbiological activity indicate that rates increase ten-fold even though water temperatures are still very cold.

Spring differs biologically from fall and winter primarily in the availability of sufficient light to make photosynthesis possible under the floating landfast ice, which is 2-meters thick by this time of year. After mid-May, direct sunlight lasts 24 hours a day. Light that penetrates into the ice warms it slightly and prevents additional freezing after May. The amount of light penetrating all the way through the ice, and so available for alga in the water underneath the ice, equals only one two-hundredth of the surface illumination. It may be reduced further by snow on top of the ice and by sediments incorporated into the ice from fall storms. Even small amounts of sediments in the ice may block light transmission completely, and hence preclude springtime alga photosynthesis and growth under the ice. Maximum springtime under-ice primary productivity, therefore, often takes place beneath the outer zone of floating landfast ice, where the ice is not as thick as the pack ice and is generally clear and covered with little snow.

Under clear ice small alga, such as diatoms, begin growing in February and by late March form a yellow-brown layer, primarily in the lowest 30 centimeters of ice. This sympagic (with ice) growth is relatively small; total sympagic algal production* is estimated to average only about one-twentieth of the total primary production of the nearshore zone. However, the production is probably very important to consumers because it occurs early in the spring when food supplies are short.

Sympagic production supports a temporary food web on the undersurface of the ice. Small benthic copepods feed on diatoms, ciliate protozoans, and nematodes; epibenthic amphipods graze the undersurface of the ice, feeding on copepods and diatoms; fishes feed on amphipods, as well as on copepods; and ringed seals eat the fishes and large invertebrates. The importance of the sympagic community as a temporary food web is indicated by the observations of Andrew Carey and his students at Oregon State University that during May, epibenthic amphipods are two orders of magnitude more abundant near the undersurface of the ice than they are near the sea bottom.

A Long and Dynamic Break-Up

Break-up of the ice cover begins in late spring, and generally takes about two-and-a-half months. First, river ice melts in late May (quite predictably), and within two weeks the rivers send half of their total annual discharge running out both under and over

* Sympagic algal production refers to the amount of energy and nutrients stored by plants associated with the ice cover.

the sea ice still clinging to shore. All of the overflowing meltwaters eventually pour down through cracks in the floating landfast ice, although they may travel as far as 10 kilometers from shore before disappearing through fissures in the ice. The transport of silt across the ice by the meltwaters perhaps accounts for the build-up of small deltas at the mouths of most arctic rivers.

The break-up process creates much turbidity in the water under the ice. Where overflow waters surge down through cracks in the ice, they resuspend large amounts of seafloor sediments, and in the process excavate depressions in the ocean floor. The depressions are called "strudel holes" by Erk Reimnitz of the U.S. Geological Survey. Strudel holes may be as deep as 8 meters and tens of meters in diameter. By late spring sediments from these strudel holes combined with the silt in river melt water have created high turbidities in the water under floating landfast ice.

Beyond the strudel holes, the relatively warm, fresh meltwaters rapidly flow outward just below the ice, riding on the denser saline waters they encounter. Fresh under-ice meltwater may flow 17 kilometers offshore, across the whole landfast ice zone. This flow dramaticallly reverses the slow winter circulation pattern described earlier.

During May and June, the increasing sunlight melts the snow cover on the ice and the sea ice gradually softens. In addition, rising meltwaters work the bottomfast ice loose from the substrate, and the ice is then moved about by wind and by the increasingly strong water currents.

Fresh run-off waters also flush out the hypersaline waters that have collected in lagoons over winter, sometimes quite rapidly. Brian Matthews and William Stringer of the University of Alaska found that salinities in Simpson Lagoon dropped from 43 parts per thousand to 0 parts per thousand in one hour on June 7, 1981, and seawater salinity of 32 parts per thousand was finally restored by early July. Salinity changes of this magnitude must create quite a stress on resident organisms, and are perhaps another reason that mobile, epibenthic organisms able to tolerate a wide range of salinities are so abundant in coastal areas.

Break-up brings other changes in the biological conditions under the landfast ice. As openings in the ice cover develop, algal production shifts from the under-ice surface to the water column. Nutrients become depleted to their lowest annual level. Primary production increases substantially; the total amount of primary production that occurs before the ice has disappeared may be as much as a third of the total annual production for coastal waters. Increases in primary production are accompanied by recolonization of nearshore areas left exposed by the release of bottomfast ice. Many small mysids, amphipods, and other epibenthic fauna move in under the newly floated ice during June. At the same time, as river channels open, anadromous fish that have overwintered in the deltas migrate out to sea beneath the floating sheet of ice. Many waterfowl and seaducks fly offshore to openings in the ice to feed on the growing populations of epibenthic invertebrates and migrating fish.

The final break-up and melting of Beaufort Sea coastal ice, and therefore the seasonal disappearance of the habitat beneath the landfast ice, may occur during early July, but in some years it may not occur at all. The time of break-up varies greatly, and is determined primarily by ice temperature and wind stress.

Usually, however, summer warmth melts the ice along the coast of the Alaskan Beaufort Sea, and a short but vital period of growth renews the populations of marine organisms. Then, a few short weeks or months later, the coastal ice sheet begins to form again, and to isolate the long, thin ribbon of under-ice water.

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The views presented in this article are those of the author and not necessarily those of the U.S. Department of Interior.

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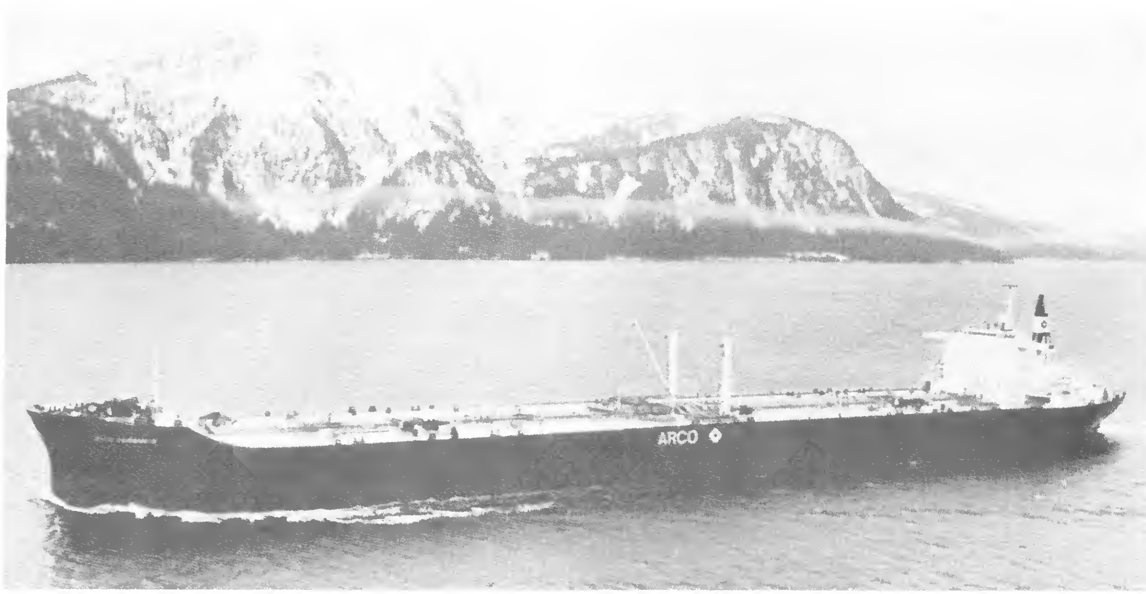


Oil tankers carrying Alaskan crude to refineries in the lower 48 states could cause substantial pollution if an accident occurred. (Photo courtesy of ARCO).

Arctic Ocean Pollution

by Vera Alexander

For centuries, the oceans have been the final resting place for many waste materials created by man. The huge volume and powerful currents of our oceans have usually diluted such wastes sufficiently to avoid harmful consequences; indeed, many assumed this was a basic fact of nature. For example, Hugo Grotius, a 17th century Dutch lawyer, argued that the seas were unspoilable in promoting his notion that they should be regarded as the communal property of all peoples. But in recent years, this longstanding assumption about the oceans and waste has been put aside; technology and population have grown to the point where even the oceans feel their impact.

Huge tankers, which transport a variety of materials across large expanses of ocean, are each capable of causing significant local contamination. Chronic release of not-easily-biodegradable materials—such as insecticides, debris, and heavy metals—turn rivers, shores, ships, and even the atmosphere into potential sources of oceanic pollution. The amount of such materials in the oceans is growing daily.

There are few people who have chosen to live in the harsh arctic climate, and the arctic seas lie far from heavy industrial activity. Consequently, there has been little concern about pollution of arctic waters until very recently. But the interconnection of the world's atmosphere and oceans means that even long-distance effects can be significant. Consider, for example, the distance of the Arctic Ocean from tropical and sub-tropical areas; but organo-chlorinated compounds that are used extensively at these lower latitudes are appearing in the fat of polar animals, including many marine animals. Heavy metals also can disperse over long distances, and may be concentrated by some species. Moreover, the progressing development of arctic resources is likely to increase pollution from local sources.

A Working Definition

Anyone who wishes to examine pollution must know what is meant by the term. In this article, I have adopted two definitions, one based on biological criteria, and the other based on human perspectives. A pollutant may be defined as "any substance added to the environment in amounts sufficient to cause biological effects." Alternatively, and more pragmatically, it may be defined as "any substance which interferes with a generally-accepted water use." A variety of substances have been identified as pollutants or potential pollutants. Some of these are described in Table 1.

Table 1. Major pollutants, their sources and impacts on arctic marine areas.

Pollutant	Source	Origin and Transport	Impact on Arctic Marine Systems
Petroleum	Municipal wastes Industry Via rivers	Long distance	Unknown
	Oil spills Production and transportation	Local	Potential local effects
	Chronic Shipping Municipal wastes, etc.	Local	Severe in coastal marine habitats
Metals	Industrial centers	Long distance Atmospheric	An emerging problem
	Mining	Local	Local effects
Pesticides	Widespread use	Long distance	Global problem
Sewage	Municipal wastes	Local	Only local effects
Agricultural	Fertilizer runoff	Primarily local	Not a major arctic problem
Noise	Seismic exploration Drilling Shipping Aircraft Helicopters	Local	Impact unknown, but is a cause for concern
Plastics	Shipping	Long distance	A serious problem
Fishing nets, etc.	Fishing industry	Local	Also a problem

Most pollutants are produced by local human activity, and therefore the most severe problems are found in heavily-populated coastal regions. Generally speaking, there are two categories of pollutants produced by human activity: municipal wastes and industrial wastes (including agricultural wastes).

Municipal Wastes in the Arctic

With the exception of a few areas close to coastal villages, marine discharge of municipal wastes has not been a problem in arctic coastal areas. However, this is mainly because of the relatively small numbers of people inhabiting the arctic coast. Sewage could cause serious pollution should the population grow substantially along the coast. Low temperatures in themselves, and even ice cover, do not preclude serious effects. For example, sewage from Oslo, Norway, dumped into the adjacent Oslofjord, causes low oxygen levels in the bottom waters of the inner fjord as well as production of hydrogen sulfide. One result has been the death of the bottom-dwelling animals.

Sewage discharge is also a problem in the Baltic Sea. The northern part of the Gulf of Finland receives treated municipal wastewater from about 800,000 inhabitants. Sewage contributes more than half of the total phosphorus entering the Baltic Sea, resulting in increased biological production. As a result, the deep waters have low oxygen content. Local eutrophication from treated sewage in the area around Helsinki has produced an increase in primary productivity, a decrease in species diversity, and a replacement of indigenous species by pollution-tolerant forms.

Oil and Industrial Development

Although the Arctic Ocean rim still has little industrial activity, the situation is changing rapidly. Petroleum development is a recent industrial activity in the Arctic, but it is now the most significant industry in the U.S. and Canadian coastal regions. Along the U.S. Beaufort Sea coast, most petroleum exploration and development has been on land. Inevitably, more offshore marine production will be developed within the decade (see page 73), and without question, the petroleum industry already has effects on the coastal marine system.

Particular concern has been expressed by the local residents, primarily Inuit,* about the effects of petroleum exploration and development on the bowhead whale, an animal of major cultural significance and one of their main food sources (see page 81). The noise created by seismic exploration and drilling (Table 2) has been a primary issue, since during their fall migration, the whales pass close to possible oil development areas. Seismic disturbances could interfere with the bowhead migration, possibly driving them further offshore, and an even more significant problem could arise if the whales were harassed by exploration in their summer feeding areas in the nearshore eastern portion of the U.S. Beaufort Sea and in the Canadian Beaufort Sea. The problem can be mitigated by avoiding specific critical areas, and restricting seismic work,

Table 2. Frequency composition and level of sound from certain equipment and activities associated with offshore petroleum operations.

Type of Equipment or Activity	Main Sound Frequency Range (Hz)	Estimated Received Level at 100 Yards (dB re 1uPa)
Bell 212 Helicopter (500 ft altitude)	0–500	100
Drillship (Canmar 'Explorer II')	0–350	133
Suction Dredge ('Beaver Mackenzie')	0–2000	120
Seismic Profiling (sleeve exploder)	0–200	180
Seismic Profiling (airgun)	0–500	180
Artificial Island ('Tarsuit', not drilling)	0–1000	—
Hopper Dredge (underway 'Geopotes X', not dredging)	0–300	146
Supply Ship ('Canmar Supplier VIII')	0–500	125

Source: Fraker, 1984.

* Inuit are the native people of Greenland, northernmost Canada and the northern coast of Alaska. Together with the Aleuts (who inhabit the Bering Sea coast of Alaska) they are commonly known as Eskimos.

exploration, and drilling when whales are present.

The Beaufort Sea coast includes barrier islands, lagoons, and river deltas. It is difficult to project the effects of oil development on these ecosystems, in part because of our inadequate knowledge of the structure and dynamics of these systems. Oil is a natural contaminant in this region, since natural oil seeps occur. Active populations of oil-degrading bacteria are present in these waters. Still, the impacts of a major oil spill would be severe, because ice-associated habitats are crucial links in the arctic marine ecosystems, and are often considered particularly vulnerable.

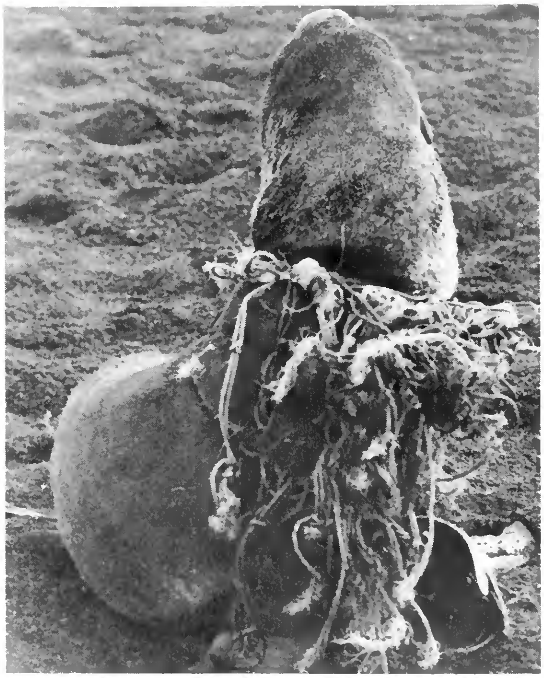
It is difficult to remove oil from ice-covered seas, and recovery is likely to be slow. Oil spills spread as a slick, and in open water are dispersed by waves and can be emulsified into a "chocolate mousse" of oil and water (see *Oceanus*, 28 [3]:2–12). Ultimately, most oil attaches to sediment and sinks, although some also evaporates.

The situation in ice-covered waters is somewhat different. Depending on the time of year, oil could remain in contact with the ice for an extended period. Oil can penetrate into the ice sheet up to 5 to 10 centimeters when brine drainage channels are open (see page 18). Paradoxically, this occurs in spring, at the same time that important biological activity takes place in this lower portion of the ice in the growth of "ice algae," a population dominated by diatoms. As the primary early spring food available to juvenile arctic cod, amphipods, copepods and other animals, this community is of key importance to the arctic marine ecosystem.

Hitherto, there has not been a serious oil spill in the Beaufort Sea. Meanwhile, a great deal of work has been done on environmental assessment of the potential effects of oil spills. A Canadian experiment, BIOS (Baffin Island Oil Spill), involved an integrated, multidisciplinary study of a 30,000-liter intentional spill. Immediate effects were found in benthic amphipods, burrowing clams, polychaete worms and sea urchins, but long-term impacts appeared minimal. The high vulnerability of the sea-ice community was confirmed, with the oil accumulating on the ice/water interface. Naturally, this is not a problem during the ice-free summer months.

Oil exploration is extending into the Bering Sea. Oil platforms, sub-sea pipelines to St. Matthews Island, and ice-strengthened shuttle oil tankers will be likely features soon in the Navarin basin. Potentially vulnerable to oil spills are extremely large breeding colonies of seabirds (kittiwakes, murres, and crested and least auklets), as well as oldsquaws, puffins, and marine mammals (including bowhead whales) which use the ice-free area to the south of Baffin Island in winter. Diving birds are particularly vulnerable, and effects can include thermal problems as the result of oiling of plumage, toxic effects from ingesting oil, and effects on eggs, chicks, and reproductive success.

In general, offshore oil production has not been a major source of oil pollution. Only the most severe blowouts cause damage. Oil spills are a very rare occurrence, although a certain number can be



Many seals, such as this one, become entangled in fishing nets and eventually are killed by this source of pollution. (Photo courtesy of National Marine Fisheries Service).

expected over the 15 to 25 year lifetime of an oil field.

Chronic contamination is also a consideration. Chronic sources include routine discharges of oil-contaminated waters, drilling fluids, and other operational discharges, as well as small petroleum spills. Severe contamination from these sources has not been found near currently producing wells. In British North Sea fields, significant hydrocarbon contamination has been found only close to platforms, where oil-based drilling muds are discharged.

In fact, the largest source of oil pollution worldwide is through river input, primarily from rivers with industries on their banks. Another source of worldwide importance is discharges from ships. There is only limited navigation in the U.S. Arctic, and in any event, oil pollution from ships has decreased. Information about the Soviet Union, which undertakes more arctic marine transportation than other nations do, is scarce.

Oil development also requires construction of roads, pads, and pipelines in coastal and nearshore areas. For example, Shell Oil Company's Seal Island project, a gravel island constructed beyond the North Slope's barrier islands, required the construction of five miles of snow and ice roads on the tundra and another six miles of offshore ice roads. Located in 41 feet of water, the island took more than 700,000 cubic yards of gravel to construct. Sources of this gravel include inland, coastal, and offshore deposits. Arctic coastlines are unstable and subject to erosion, and the effects of removing gravel for such projects can be significant, although most gravel used for construction is from

Aerosols form the "Arctic Haze," an atmospheric contamination transported as shown from industrialized areas. (After Rahn and McCaffrey).

onshore. Even more serious is the interference of along-shore water movement by causeways.

Mining

The Soviet Union has by far the most active arctic mining operations, although little of the industry is coastal and therefore likely to impact the arctic marine environment. Tin, gold, and lead are mined near the coast. It is difficult to assess whether or not significant quantities of pollutants are released directly, or indirectly, into the Arctic Ocean by Soviet operations. Heavy metals, in general, are often carried down river from mining operations and industrial processes.

Two major high latitude coastal mining activities for which information is available are coal mining on Svalbard Island and lead/zinc mining in western Greenland at Maarmorilik (the Black Angel Mine). Tailings from this mine, located 500 kilometers north of the Arctic Circle, are discharged into Agfardlikavsa Fjord at the rate of 468,000 tons per year. The lead and zinc which remain in the tailings occur as insoluble sulfides and should cause no problem. However, a larger amount of metals than expected are released while the tailings are suspended in the water. Seaweeds and mussels both showed increased metal content as a consequence of this disposal. This potentially serious pollution problem was countered by removing more of the metals from the ore and also by decreasing the solubility of the tailings. Consequently, the metal content of the fjord is decreasing. Fairly rapid recovery can be expected when the mining ceases, assuming that the tailings in the fjord remain undisturbed. Another lead/zinc mine is located at the north end of Baffin Island (Nanasivuk Mine). This mine has been in operation since the mid-1970s, and also has dumped tailings into a fjord.

Apart from such local situations, it turns out that relatively high concentrations of zinc, cadmium, copper, and aluminum are found in the surface waters of the central Arctic Ocean. Although not at "pollution" levels, their source is not understood. Input by rivers is a possible answer, but this cannot be confirmed because we lack information on the concentrations of these elements in river waters. The Arctic Ocean is fed by very large rivers and the contribution of contaminants by the Soviet Union's rivers is a major unknown. A 300-fold increase in lead content over that in ancient arctic and antarctic ice has been attributed to industrial sources. Transportation in this case is almost certainly by atmospheric processes. Metal pollution is thus becoming a serious global problem.

Plastic Pollution

A large amount of plastic trash is accumulating in the world oceans, much of it derived from marine transportation. Polyethylene and polypropylene industrial pellets are found in densities as great as 1,000 to 4,000 per square kilometer on the surface of the North Atlantic, South Atlantic, and Pacific Oceans. This material is not readily broken down, and tends to accumulate.

Some seabirds injest large quantities of this material, and although this problem has not extended to the Arctic Ocean, it is becoming evident in the Bering Sea. The impact of such pellets on seabirds is not clear. Fishing gear, especially nets (often lost from boats and "ghost-fishing"), can kill seals. Other materials, such as metal straps from packing crates, also can cause damage. There is already a 6 percent a year decrease in the northern fur seal population. Apparently, the young are frequently found ensnared in fishing gear—the loss amounts to thousands of seals per year, perhaps as many as 30,000. The subarctic seas are noted for their abundant seabird and marine mammal populations, and this accumulating material is likely to be an increasing hazard.

Long Distance Transport

Even though the arctic coast has limited industrial activity, industrially-produced contaminants, transported over long distances by atmospheric processes, apparently do reach the far north. High concentrations of mercury and cadmium have been found in tissues from seals and fish in Greenland; and in the case of mercury, the resulting exposure level of some of the human population is sufficiently high to produce subclinical effects. Mercury concentrations tend to be highest in fetuses and newborn children.

The blood lead content of Greenlanders is surprisingly high, comparable to that found in Western European industrial cities, and the same is true for selenium, especially in western districts.

One possible explanation is that this contamination is the result of long distance transport of airborne particles. This is likely, since the so-called "Arctic Haze" has become a common phenomenon in the atmosphere of arctic Alaska. This atmospheric contamination, in the form of aerosols, is of continental origin and pollution-derived. It is markedly intensified in the winter. Identified sources include the Far East countries, Europe, Siberia, and North America. Atmospheric sulfate has been found at concentrations of 1 to 3 micrograms per cubic meter in Barrow, Alaska; this level is at least 10 times higher than normal background levels in such unpopulated regions. These materials, in addition to direct fallout, also accumulate in the Arctic Ocean through land drainage and river transport.

Marine processes also can transport pollutants. For example, agrochemicals and chlorinated pesticides are carried from northern European coastal areas into the Barents Sea, and probably into the Arctic Ocean. Eutrophication resulting from runoff from agricultural lands is a serious problem along the North Sea coast of Denmark, and it is likely that some of this input is also moving northward toward the high latitude seas.

The Baltic

The Baltic Sea, a cold water sea which is partly ice-covered in winter, is one of the world's most severely polluted seas. Industry is a primary cause (petroleum, paper, and pulp), with significant contributions from agricultural fertilizers and polychlorinatedbiphenyls (PCBs). The severity of the problem results from very low rates of water exchange between the Baltic and other seas. Consequently, bird populations have decreased as the result of eggshell thinning. The grey seal population also has decreased because of reduced reproductive capacity caused by PCBs accumulated in Baltic herring, their primary food. Many Baltic pollutants persist for a long time.

Epilogue

The Arctic is often identified as particularly vulnerable to the effects of pollution and disturbance connected with large-scale development. Hitherto, however, the most visible effects have been from pollutants transported over vast distances, primarily through the atmosphere. These are difficult to assess. The purely local effects of new development are subject to scrutiny and control. They are less likely to cause long-term impacts.

Inevitably, development will take place, and problems will surface, but the question of whether arctic marine ecosystems are particularly vulnerable because of climatic extremes and slow turnover of biomass has not yet been answered.

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Major river inputs to the arctic ocean.

U.S.S.R. (discharge rates >30 cubic kilometers per year)	
Severnaya-Dvina	110
Pechora	130
Ob	395
Yenisei	550
Lena	490
Yana	30
Indigirka	60
Kolyma	120
Alaska & Canada (discharge rates >10 cubic kilometers per year)	
Yukon	200
Kobuk	20
Colville	12
MacKenzie	240

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Arctic

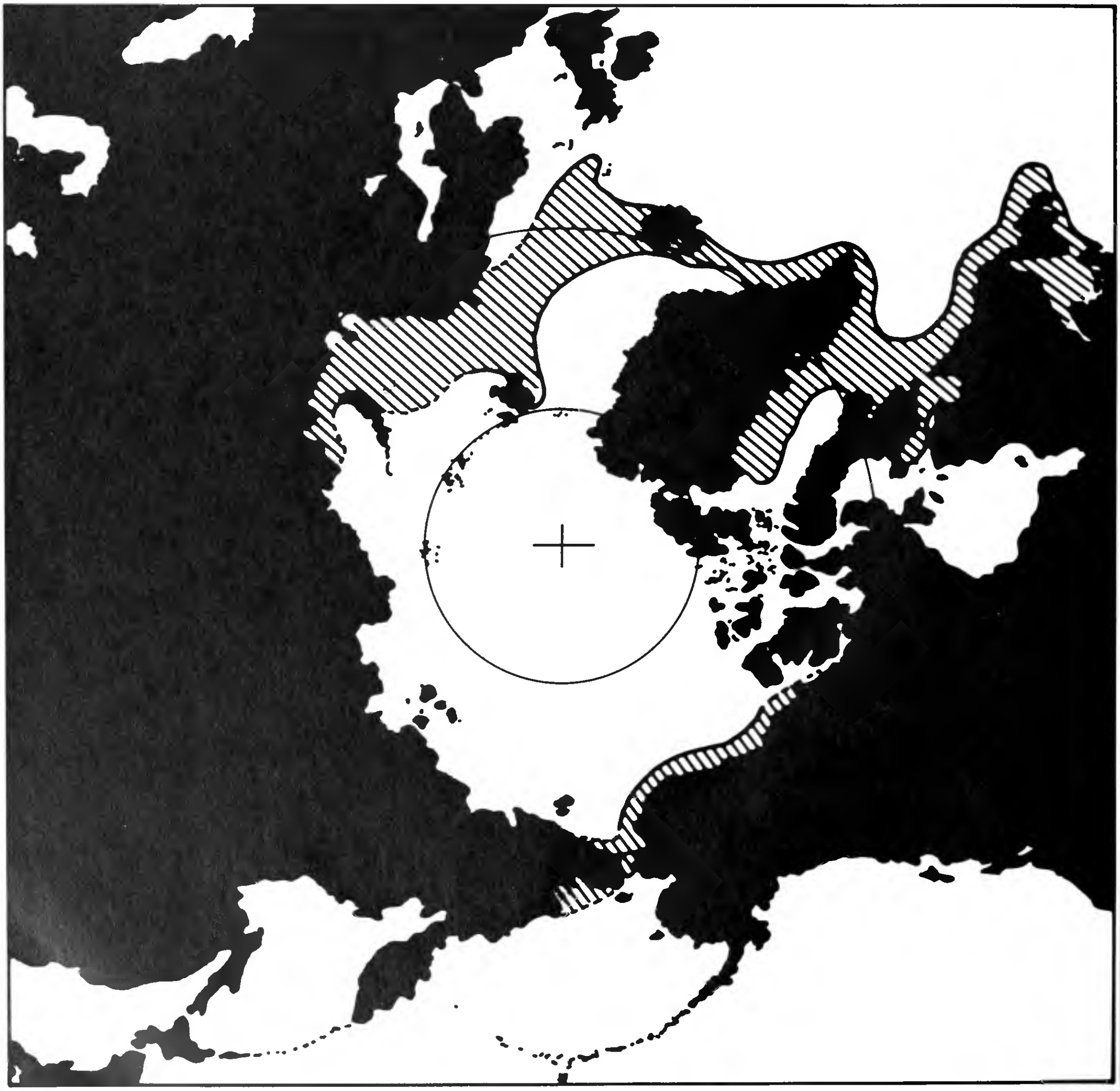

Figure 1. Marine Arctic and Subarctic regions. The shaded area is the Subarctic as defined in this article.

Marine Ecosystems

by M. J. Dunbar

The Antarctic Ocean is among the more biologically productive areas of the world's oceans while the Arctic ranks among the poorest—yet each is as cold as the other. The key to this difference in productivity resides in the oceanographic structure of the water column in these oceans which either encourages or discourages the return of plant nutrients (phosphates, nitrates, silicates) to the sunlit layer at the top. It is this factor that makes it essential to begin by defining the Arctic Ocean.

Polynyas are a favorite watering spa for polar bears. (Photo by Dan Guravich, Photo Researchers)

The Arctic Circle, of course, has nothing to do with the matter. This is especially true of the sea, in which warm and cold currents penetrate north and south for great distances. Historically, the terms Arctic Ocean or Northern Ocean, have been used in a somewhat loose geographic sense, usually including regions such as the Bering Sea, the Barents Sea, Baffin Bay, and the Greenland and Norwegian Seas, in addition to the central Polar Basin itself. This satisfied the need of the navigator and the casual geographer; there was a general similarity over the whole area in terms of weather, ice cover and, until the Polar Basin was explored, a similarity between the larger fauna. The work of oceanographers and fishery scientists in the north gradually made it necessary to be more precise. It became clear that there were important differences between the Polar Basin, or Arctic Ocean proper, and the peripheral seas, and even between the several seas.

The two most significant differences are ice cover and vertical stability of the water column. Most of the Central Basin is ice-covered throughout the year. It is estimated that some 75 percent of the total area is covered by old, multi-year smooth ice; about 10 percent with "hummocky" or rafted ice; about 8 to 17 percent with first-year ice; and less than 1 percent is open water. These numbers are approximate, and vary slightly from year to year. The melting and re-formation of the ice, daily and seasonally, have a thermostatic effect—for example, the temperature of the water immediately below the ice remains almost constant. Animal life in the upper 50 to 75 meters of the water column is largely dependent on diatoms and other plant cells endemic to the ice itself.

The upper 200 meters of the central Arctic Basin in the strict sense is termed "Arctic water." It flows out of the Arctic Ocean in approximately equal amounts by two main routes: through the Arctic Islands of Canada and down the East Greenland coast. The Arctic Marine Zone is the area in which "Arctic water" is unmixed with water of another origin. Atlantic and Pacific waters eventually mix with this water and also penetrate the Arctic Ocean at depths below 200 meters. Areas in which mixtures of arctic and non-arctic (Atlantic or Pacific) water occur are defined as the "Marine Subarctic." Further southward, where the presence of arctic water is no longer discernible, is termed the Boreal or Temperate zone.

There are good biological reasons as well as hydrographic reasons for this zonal differentiation. Subarctic water is not vertically stable and the production of life can be very high. Figure 1 shows the Arctic-Subarctic zonation, and Table 1 gives a comparative summary of marine productivity on the global scale. The global map of biological production in the sea is largely the map of vertical stability-instability. Some of the most important fisheries are developed in the Subarctic, notably the Atlantic cod, salmon, redfish, and capelin.

Table 1. Primary phytoplankton production estimates from different geographic regions, compiled from various sources. Numbers are grams carbon per square meter per year.

Arctic Ocean	0.6–5
Dumbell Bay, Ellesmere Is.	9–12
Off Cornwallis Is.	15, 32
Beaufort Sea	9–18
Northeast Chukchi Sea	18, 28
Frobisher Bay	41, 70
Bering Sea (shelf)	250
Bering Sea (oceanic)	75
Lancaster Sound	74
"Subarctic Pacific"	35–100
Gulf of Alaska	48
Barents Sea	25
Davis Strait	50
West Greenland, three locations	29, 95, 98
West Greenland (Disko Bay)	36
Jones Sound	20, 35
Gulf of Finland	30–40
Akkeshi Bay (Oyashio Current)	295
Sendai Bay, Japan	100
Suruga and Sagami Bays, Japan	90
Seto Inland Sea, Japan	127
St. Margaret's Bay, Nova Scotia	190
Gulf of St. Lawrence (main Gulf)	212
Gaspé Current, G. of St. Lawrence	385
Lower St. Lawrence Estuary	509 (?)
Strait of Georgia	120
Off New York	100–160

Biological Significance of Ice

Not long ago the Arctic Ocean was considered to be rather dull, uniform, and of little scientific interest. This view has changed significantly in the last decade or two with recognition that the permanent ice cover (which itself is not uniform), the marginal zone of broken and temporary ice, the polynyas (areas more or less ice-free in winter) and the ice edge, constitute different habitats and conditions for life, and are different in physical behavior. The marginal ice zone has been the subject of intense study in the Greenland Sea and the Bering Sea since 1983, with the realization of the Marginal Ice Zone Experiment (MIZEX) [see *Oceanus*, Vol. 26, No. 2, p. 55], the culmination of much preliminary work. In fact, attention has been focused on ice-edge phenomena for many years.

Navigators in the past have remarked on the sudden increase in life that appears as soon as the ice edge is approached; birds, seals, and whales tend to concentrate in this region. It was suspected that there must be upwelling along the ice edge. In 1979, wind-driven upwelling was demonstrated on a large scale in the Greenland Sea. Upwelling also has been indicated in the North Water, the large polynya in Smith Sound and northern Baffin Bay. The team that has been studying this region by airborne methods, based at McGill University in Canada and at the ETH Institute in Zürich, Switzerland, has recorded sea-surface temperatures in winter well above the freezing point, clear indication of the advection of heat from below. Plans are now in progress to study this polynya from shipboard, something that has not yet been done.

But upwelling is not the only mechanism required to produce phytoplankton blooms. It is also necessary, after the upwelling process, to establish a stable upper layer to contain the phytoplankton—that is, to prevent it sinking out of the euphotic zone (the surface to 80 meters or more). This process also is accomplished by the marginal ice zone, following

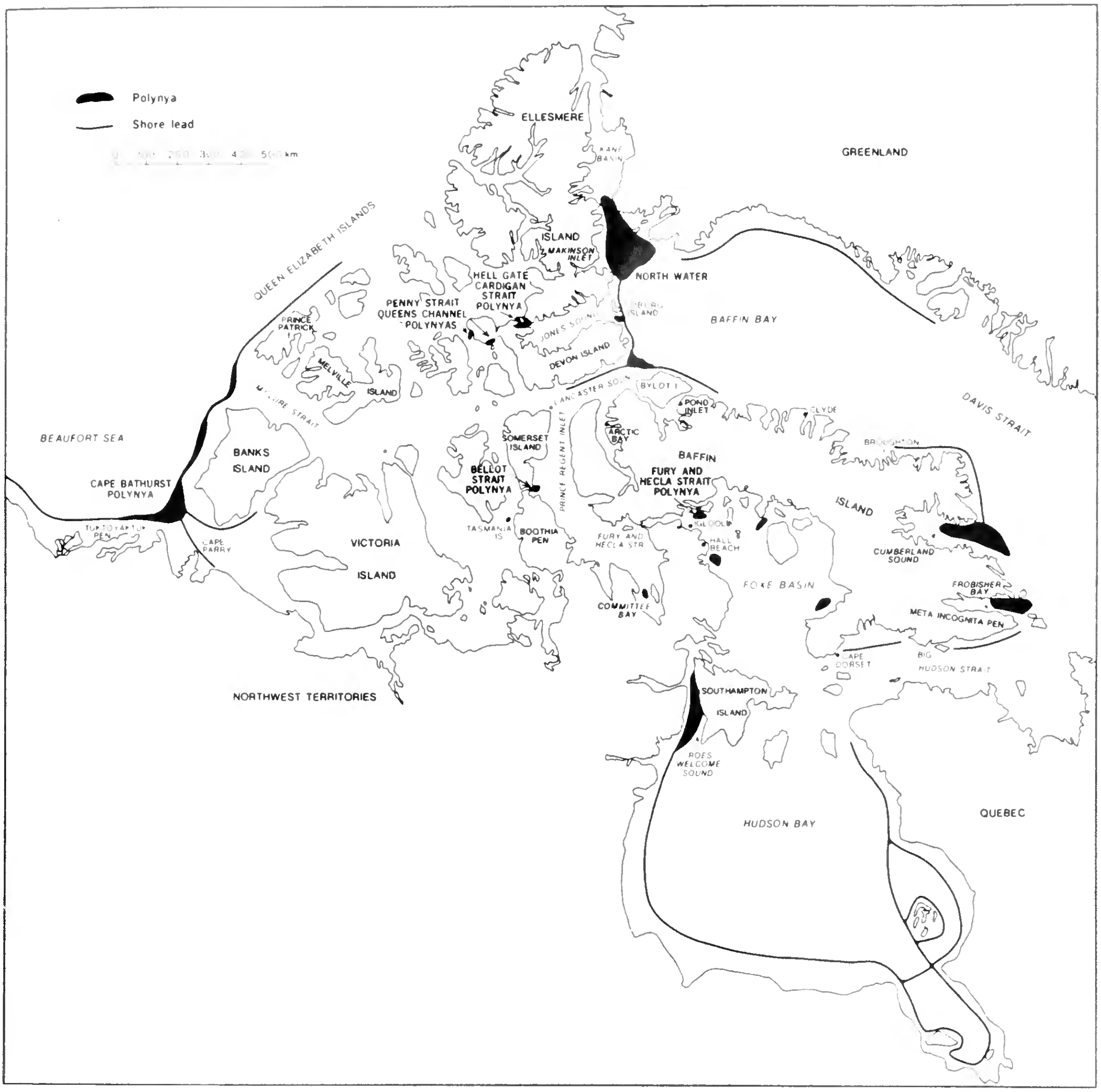

Figure 2. Polynyas (dark areas) in the Canadian North. (From Canadian Wildlife Service, Occasional Paper No. 45, 1981)

on the rapid melting of the ice in spring. As the edge of the ice recedes, this condition of high production continues over an increasing area.

Polynyas constitute a special case, both physically and biologically, and their great ecological importance is only beginning to be recognized. They provide winter refuges and feeding areas for walrus, certain seals, and polar bears. Whales do not use them, except by accident; they migrate out of the winter ice-covered regions. Polynyas provide open water for seabirds on migration. Probably their greatest significance lies in upwelling. The upwelling function is manifested not only in wind-driven upwelling, but also in a vertical exchange mechanism that is not yet fully understood.

This mechanism seems to have been first suggested by Russian researchers. The thesis is as follows: 1) polynyas are caused by winds for the most part, but they also are ice factories, the ice being constantly blown downwind; 2) the constant ice formation, which leaches out salt to the water below, causes high salinity at the surface; 3) the result is sinking, with vertical exchange of water between the surface and depth; 4) this vertical exchange in regions where there is an underlying layer of Atlantic (or Pacific) water, reaches down to the warm water, bringing heat to the surface. Similar thermohaline convection is postulated for antarctic polynyas.

This mechanism may be the explanation for the surprising biological fertility of Lancaster Sound, which lies downstream from the North Water (see Table 1). The North Water, and other large polynyas, may function as winter "nutrient pumps," influencing marine areas well beyond their own limits. Figure 2 shows the distribution of polynyas. This Lancaster Sound measurement is broken down as 11 grams carbon per square meter per year from the ice algae, 25 grams carbon from the spring phytoplankton bloom, and 38 grams carbon phytoplankton later in the season. The measurement of primary production in the ocean is still "in its infancy," and probably gives us numbers that are far too low. Nevertheless, the general geographic pattern shown is reasonably reliable. The study of the production of attached algae (seaweeds) in northern waters has been neglected. The production of benthic diatoms also has not been given close enough attention.

The literature on the ice biota system—that is, the special ecosystem or subsystem based on plant growth within the ice—is now very large. I would draw attention to two recent papers by Mel'nikov. Both papers are concerned entirely with the ice of the Central Polar Basin, and demonstrate how important the ice system is in the total biological production of the Arctic Ocean.

Mel'nikov distinguishes between an endemic flora, consisting of Chlorophyta and Cyanophyta, which leaches downward through the ice from the snow above; and a non-endemic flora (dominated by diatoms), which develops at the bottom of the ice and is planktonic in origin. As the ice thickens in the fall, the diatoms are carried into the body of the ice. Dying within the ice, they form a source of energy for the development of the endemic, or year-round, flora, so that the energy path is upward in the ice column. The associated fauna, mainly amphipod and copepod planktonic Crustacea, also are partly permanent and partly seasonal.

Ecosystem Evolution

Ecosystems have evolutionary or developmental histories. Global cooling, which began in Miocene-Pliocene times (11 to 12 million years ago), must have put gradual constraints on the high-latitude ecosystems of both land and sea. The onset of the Pleistocene glaciation (about 2 million years ago) was undoubtedly a shock. The ice-edge events and processes during the glaciation must have been extremely active, if only because the temperature gradient between Arctic, Pacific, and Atlantic waters probably was very steep. We have little information on how or in what volume the Atlantic water penetrated into the Arctic Ocean at that time, but clearly during interglacial periods, of which the present Holocene time is the most recent, the situation would have been similar to what it is today.

The influence of Atlantic water in the Arctic Ocean, where it forms a layer roughly between 200 to 900 meters, and the fact that it is much greater in terms of volume than is the Pacific influence, have led to the conclusion that the Arctic Ocean is nothing more than an extension of the Atlantic. In fact, it is very much its own entity.

Shifts in faunal distribution are with us all the time, mainly the result of climatic changes analogous to events in the more distant past. During the last century, there have been dramatic changes, for example, in the fauna of the Subarctic-Atlantic region, including Baffin Bay, the Greenland Sea, Iceland, and the Norwegian and Barents Seas. In economic terms, these have manifested themselves in the rise and fall of cod fisheries in Greenland waters and in the Svalbard area, the appearance of Atlantic salmon in very large numbers in Davis Strait from the 1950s onward (and their apparent retreat in the last three years), and in fluctuations in the capelin and herring fisheries. In fact, there have been oscillations in whole marine regional ecosystems. The current extremely interesting changes in atmospheric carbon dioxide content should be followed with close attention, but this applies also to climatic changes dependent on natural cycles rather than on human activities. The natural forces seem at present to be pushing these subarctic waters toward cooler rather than warmer conditions.

Finally, there is the matter of the "fragile Arctic." This phrase seems to have been coined not by scientists but by politicians and the media. It is a catchy phrase and has been widely adopted, giving rise to public misconceptions. I can see little reason to believe that arctic ecosystems are any more or any less vulnerable to human disturbance than other ecosystems, land or sea. A really fragile system exists not in the north, but in the tropical rain forest. However, arctic systems are usually simpler than others, involving lower diversity of species, so that extinction of a given link in the food web might be considered serious. On the other hand, the numbers of individuals within species are larger. Moreover, the same ecosystem extends over very large geographic areas, as on the tundra or in the sea, so that damage in one region can be repaired by immigration from adjacent regions. In fact, arctic systems appear to be just as tough as others. Small lakes, permafrost, and the subarctic forest are examples of terrestrial systems that have to be treated with care and understanding. The marine system though, does not show special cause for concern. It is part of the world ocean.

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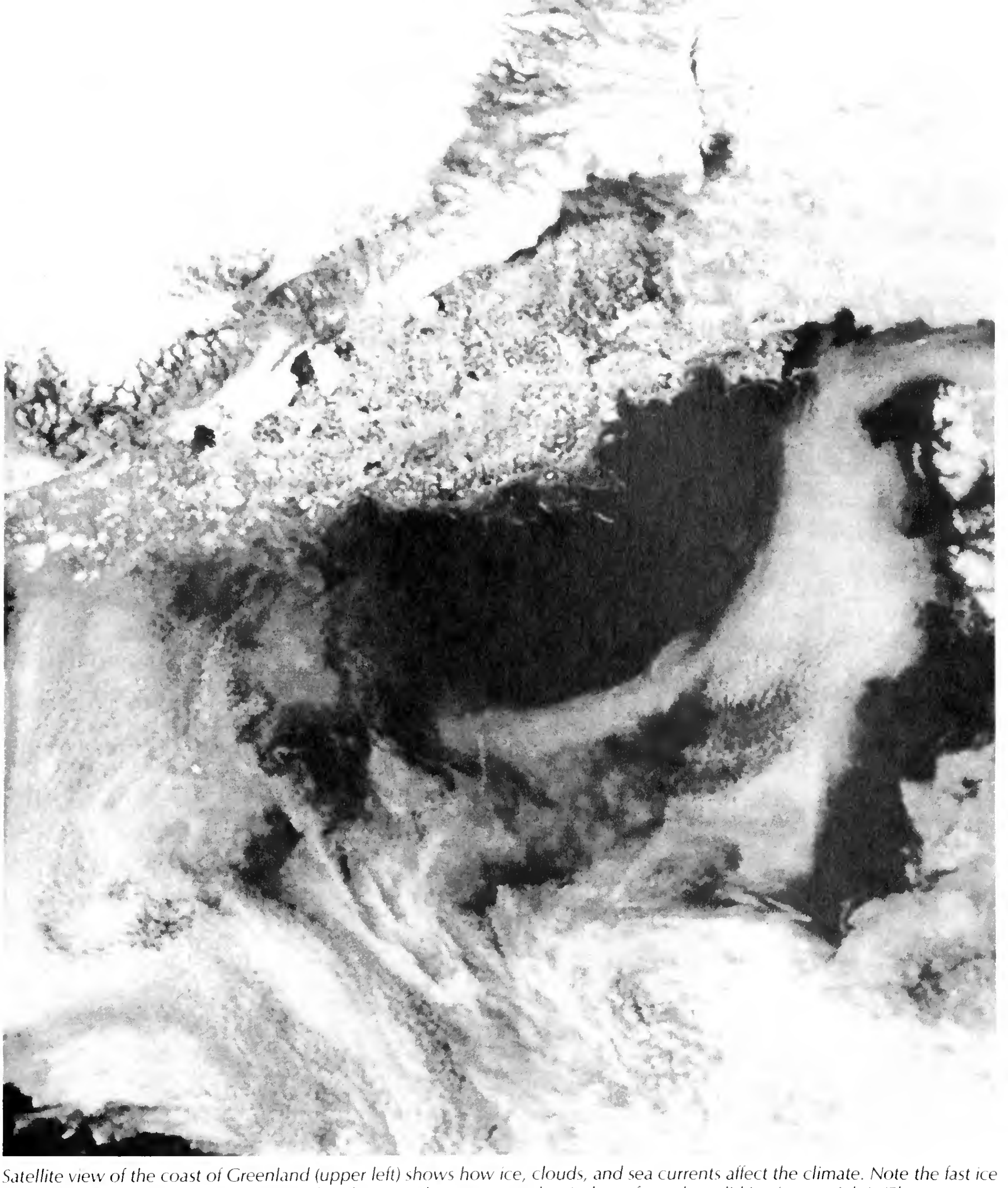


Satellite view of the coast of Greenland (upper left) shows how ice, clouds, and sea currents affect the climate. Note the fast ice attached to land and the floe ice which breaks up as the current pushes it down from the solid ice (upper right). (Photo courtesy of the Office of Naval Research.)

The Arctic's Role in Climate

by D. James Baker

The polar regions play a special role in climate. Interactions of ice with the atmosphere and ocean determine polar climate, and the ice itself is a sensitive indicator of climate change. Moreover, the ice contains a unique and undisturbed record of past climate, a record that helps us put our own climate in perspective. Figure 1 shows the processes responsible for air/sea/ice interaction in the polar regions. In this article, I address two major climate effects: the role of the Arctic in the global energy balance, and the feedback mechanisms involved in

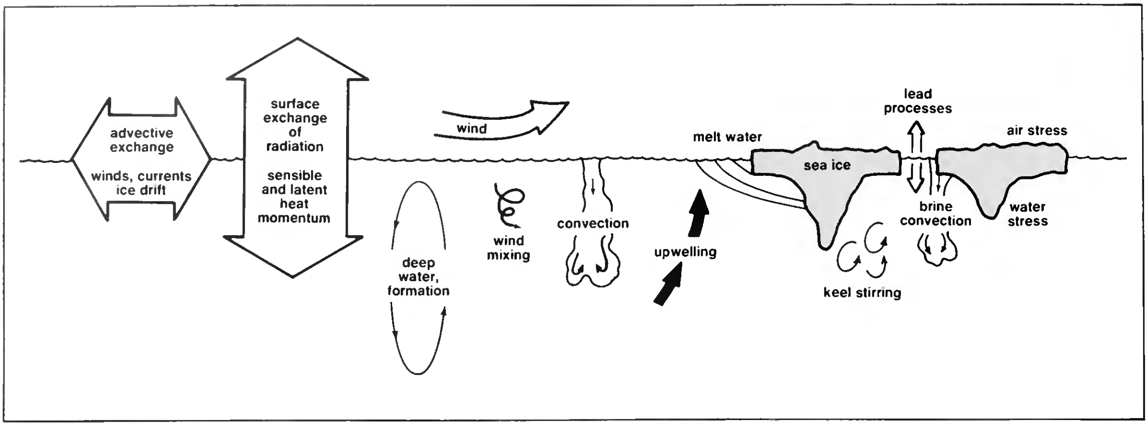


Figure 1. Air/sea/ice interaction. (From P. Lemke, in press, 1986)

maintaining that balance. An example is the effect of increasing CO_2 in the atmosphere on polar climate.

The Global Energy Balance

Warmth from the sun is the energy that makes the Earth habitable; but that warmth is not distributed uniformly. Because of the spherical shape of the Earth, most of the sun's radiation is received directly at near-normal incidence in the tropical regions; little is received in the polar regions because the Earth curves away from the direct rays. Moreover, more radiation is reflected from the polar regions by ice and persistent cloudiness. The outgoing radiation from the Earth, on the other hand, varies much less with latitude than the incoming. In the tropics, the clouds and water vapor that are the principal radiators are at a high, cold altitude; in the polar regions, the radiating water vapor is at a lower, relatively warmer altitude. The net result is nearly uniform radiation from the Earth with latitude. Since the polar regions radiate nearly as much as, but receive less radiation than, the tropics, there must be a net transport of heat into these regions.

This poleward transport of heat is carried by the circulation of the atmosphere and the oceans. The circulation is driven by sunlight absorbed by the ocean, which in turn heats the atmosphere from below. The subsequent convection drives the whole system of atmospheric circulation with its trade winds, jet streams, and storms. The atmospheric circulation in turn drives the ocean circulation by wind stress at the surface: hence, the broad equatorial currents that flow to the west in the direction of the trade winds, but which are deflected to the north or south in each hemisphere by the continents to form the Gulf Stream, the Kuroshio, and other major warm western boundary currents.

The ocean is also driven directly by the heating and cooling at its surface, a process that is most effective in the polar regions, since cooling causes sinking, which in turn leads to deep, cold currents. The warm, northward-flowing Gulf Stream and Kuroshio are important means of poleward oceanic heat transport, but another is the cold, southward-flowing deep waters that are formed in the seas bounding the Arctic Ocean. The cold, dense water that is formed in the Greenland Sea and that flows out to the North Atlantic from the Denmark Strait and over the Scotland-Faroe Ridge is thus a significant element in the global heat balance. Figure 2 shows some of these processes at work.

The net effect of the atmospheric and oceanic circulation is to carry heat poleward, thus cooling the tropics and warming the polar regions. At latitude 25 degrees North, the atmosphere and the ocean carry about the same amount of heat poleward, whereas at 60 degrees North, because of continental barriers to the ocean, the atmosphere carries most of the heat. The over-all system can be viewed as a heat engine that receives heat at a high temperature and rejects it at a slightly lower temperature. The work done maintains the circulation against dissipation.

With the stage set globally, let us look at the special role of the Arctic in climate. Net heat loss through radiation leads to the formation of glaciers and the Greenland ice cap; the seasonal formation of snow; multi-year ice in the Arctic Ocean itself; and sea ice around the edges of the Arctic Ocean, Bering Sea, and Greenland Sea. The interactions of this snow and ice with the atmosphere and ocean are the primary factors determining climate and climate change in the Arctic.

Feedback Mechanisms

The interaction of processes that can lead to amplification or diminution of a particular effect is called feedback. Warming leading to further warming is called positive climatic feedback; warming leading to subsequent cooling is called negative climatic feedback. The physical processes involved in arctic climate dynamics can lead to either positive or negative feedback, depending on which process dominates. There are many such processes and linkages among processes.

Because of the high reflectivity of sea ice, any warming process that leads to melting reduces the amount of energy reflected and thus increases the amount of energy absorbed by the Arctic Ocean.

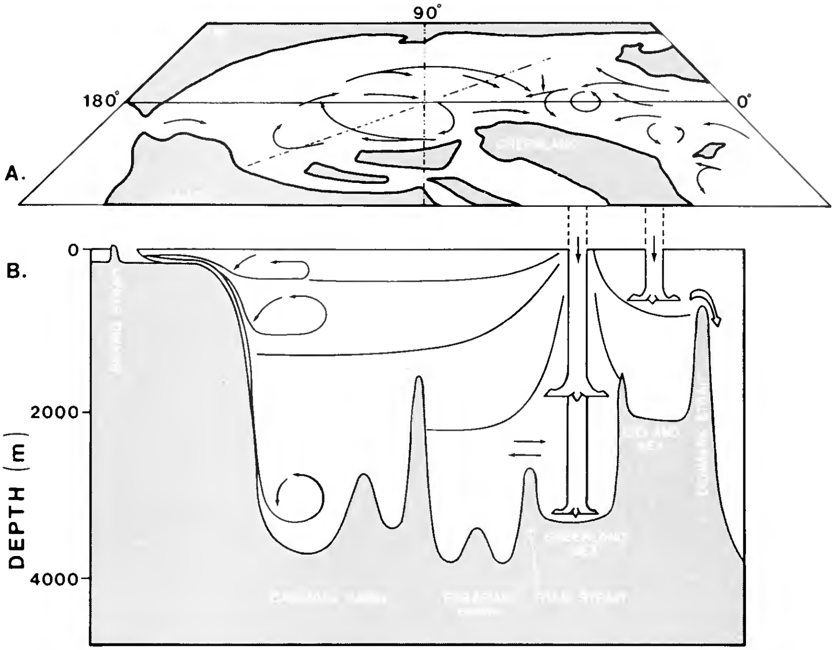


Figure 2. Circulation and water mass structure in the Arctic Ocean and nearby seas. (From K. Aagaard, J. H. Swift, and E. C. Carmack, 1985.)

Thus the ocean will become warmer, and potentially more ice would melt. This is a positive feedback system. Model calculations show that the sea-ice feedback amplifies the sensitivity of climate to small temperature changes by about 25 percent. Such a situation occurs every year, when winter turns to summer. The increased warming melts the seasonal sea ice, and more and more warmth is absorbed by the ocean.

Could the Arctic completely melt in summer, and if so, would the ice remain melted in winter? This question has been asked many times, but we still do not know the answer. We do know that the arctic ice has been an extremely stable climate feature. Geological evidence supports the existence of an ice cover back to at least several million years ago. It is possible that the Arctic was open earlier, but we do not have direct evidence for this.

Model results have shown that a warming of the atmosphere of about 8 degrees Celsius during the summer would be sufficient to melt all the ice. Other models have shown that even if the ice completely melted in summer, there is such a strong cooling in winter that a year-round open Arctic could not exist. The problem is that all of these models are relatively crude, not including changes in cloud cover, ice dynamics, open leads, or oceanographic effects. For example, the relative amounts of heat carried poleward by the atmosphere and the ocean must be known before the feedback effects can be fully understood.

Although the ice does not disappear during the arctic summer, it does melt back. There is a lag between the time of maximum heating or cooling and the ice extent. Figure 3, taken from a 25-year average (1953–1977) of arctic sea ice, shows that the maximum ice area occurs in late February or early March, and the minimum in late August or early September. This lag, about two months, is the result of the natural response time of the ice and the heat stored in the ocean below. An analogous effect occurs with polar snow. The advancing snow line closely follows the decreasing radiation at the end of summer, but lags behind the increase in spring as a result of the thermal inertia of the snow.

Because of the relatively large amount of snow cover in arctic regions, a small change of sunlight at high latitudes in the late summer can produce a relatively large change in reflected radiation and hence temperature. For this reason, it is believed that the Milankovich effect that relates ice ages to changes in the orbit of the earth on millennial time scales operates more effectively on

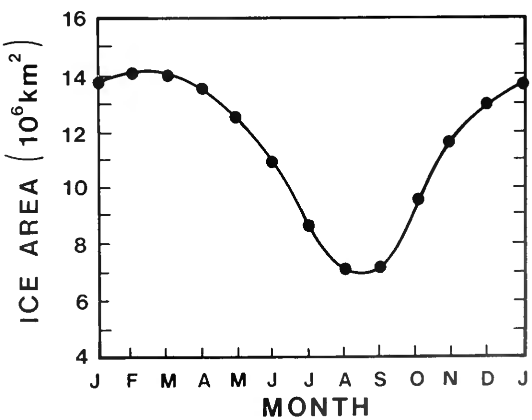


Figure 3. The normal seasonal cycle of arctic sea ice extent. (From J. E. Walsh and C. M. Johnson, 1979.)

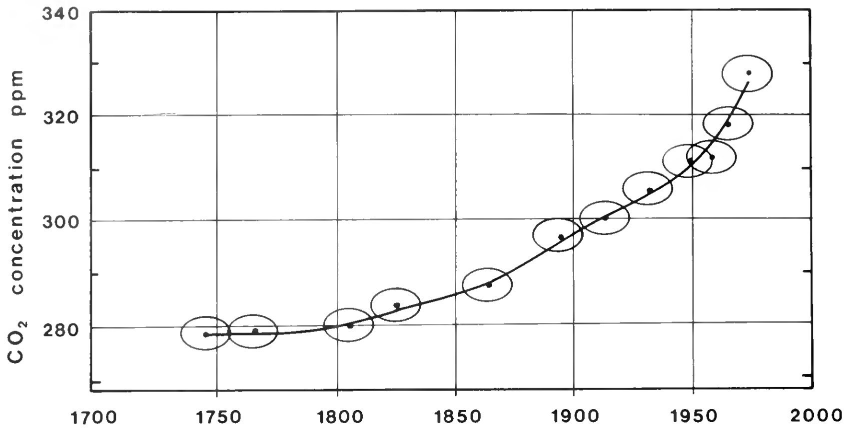


Figure 4. Atmospheric CO_2 concentrations measured in glacier ice formed during the last 200 years calibrated against the Mauna Loa record for the youngest gas sample. (From Neftel, A., Moor, E., Oeschger, H., and Stauffer, B., 1985.)

the snow in the Northern Hemisphere than on the sea ice in the Southern. It is relatively easy to incorporate the effects of changes of polar snow and ice into models of climate change. It is not so easy to include related reflection and absorption effects involving the breakdown of the crystalline structure of snow and the formation of melt ponds on sea ice, but these are also believed to be important. Ice-cap-radiation feedbacks also occur on Mars, where every winter frozen carbon dioxide and small amounts of frozen water cover the ground from the pole to about 45 degrees latitude. The feedback effect is estimated to be as large on Mars as it is on Earth.

Oil spills also can lead to a feedback effect. The dark oil on the surface of the ice absorbs heat, and can lead to local melting. Thus major oil spills could have local climatic effects. Other examples of feedback mechanisms include changes in cloudiness with the accompanying changes in reflectivity and absorption, and the interactions between oceanic and atmospheric circulations (for example, if wind stress decreases, heat flux northward by ocean currents would decrease, leading to stronger latitudinal temperature gradients in the atmosphere and possibly stronger winds).

Effects of Increasing CO_2

Strong evidence exists that the concentration of carbon dioxide is increasing in the atmosphere. Figure 4 shows the atmospheric CO_2 concentrations since 1750; the data for the first 200 years are from CO_2 concentrations measured in glacier ice; for the last 30 years from direct measurements of atmospheric concentration. At this rate of increase, the atmospheric concentration would double in about 50 years.

Since carbon dioxide is a good absorber of infrared radiation, an increased concentration leads to a warmer Earth. Moreover, several other gases produced by man, also with the same absorbing properties as CO_2, are increasing as well. These also lead to a warmer earth. The best models show that the Earth would warm, on the average, about 2 degrees Celsius in the next 50 years if the concentration of these gases continues to rise at the same rate. The global consequences of an average temperature rise of this magnitude are significant; the regional consequences could be severe.

With an increase of radiatively active gases, there is an over-all warming of the Earth with a stronger warming in the polar regions. Figure 5 shows a model result with a doubling of CO_2 in the atmosphere. The first reason for the intensification is that the arctic atmosphere is more stongly stratified than the mid-latitude and tropical atmosphere, because the arctic surface is colder. A stronger stratification makes vertical mixing more difficult. Hence, when increased radiation is trapped by the radiatively active molecules in the polar regions, the heat is trapped closer to the surface. As a consequence, the surface warms more than it would if the heat were distributed through more of the atmosphere. The second reason is a feedback effect: as the increased warming melts the polar snow and ice at the boundaries of the polar regions, the ground and the ocean absorb more heat, and the warming is intensified. The two effects are roughly equal in importance. Models show that if the average warming over the globe is 2 degrees Celsius, the amplification effects lead to polar warming of as much as 10 degrees Celsius. As noted earlier, this amount could be enough to melt the arctic ice cover.

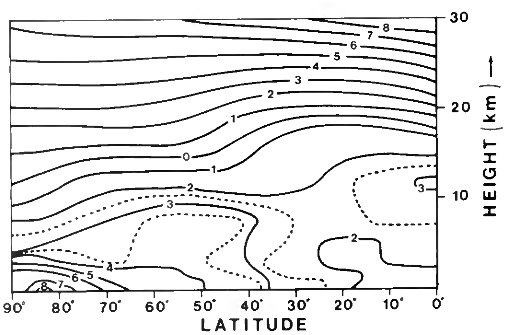
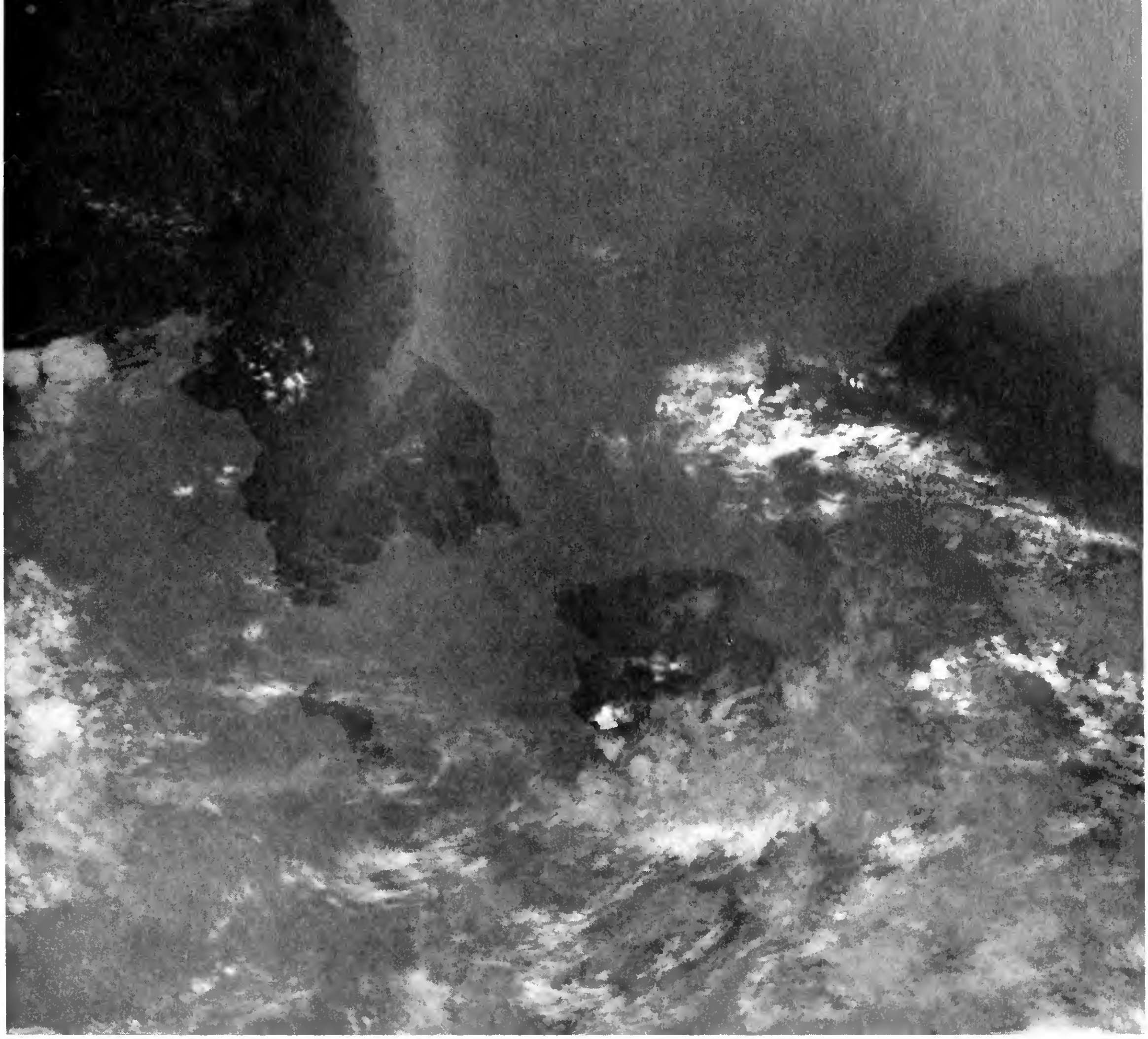


Figure 5. The mean temperature difference between a model of the atmosphere with the current CO_2 concentration and one with the CO_2 concentration doubled. Note the increase in surface temperatures at the higher latitudes, near the Arctic Ocean surface (at left). (From Wetherald, R. T., and Manabe, S. 1979.)



The Bering Strait runs in between the Soviet Union (upper left) and Alaska, connecting the Chukchi Sea with the Bering Sea. The climate of these polar regions is affected by air/sea/ice interactions. (Photo courtesy of NOAA/Navy Joint Ice Center)

The warming could be detected through measurements of the changing sea-ice extent, but other techniques are possible. For example, it has been suggested that lake freeze-up and break-up records in arctic regions could be used as a temperature indicator for detecting climate change. Changes in glacier motion, that is, the so-called "surges" or fast-moving ice streams on Iceland or Greenland, could also be used.

Water vapor, consisting of molecules that have many degrees of freedom and are good absorbers of heat, also creates a feedback effect in the polar atmosphere. As the temperature increases globally, the warmer air will be able to evaporate more water at mid-latitudes. As relatively more moist air is carried to the polar regions, it absorbs more radiation, thus decreasing the net radiation loss. Thus the temperature increase leads to an additional temperature increase.

This large warming could lead to the melting of the sea ice in the Arctic Basin. If that occurred, the Arctic Basin would then appear dark rather than white to incoming radiation. The darker water surface would be a good absorber of heat, leading to even further warming and thus loss of all of the ice. However, at the same time, the increased water temperature leads to increased evaporation and hence the possibility of increased cloudiness in the region. The increased cloudiness would in turn be a better reflector of radiation, and thus cooling, since less heat would reach the surface. Clearly, both positive and negative feedbacks are present in the arctic climate system.

The oceans near the Arctic also affect the cycle of CO_2: the formation of cold, dense water in the Greenland/Iceland/Norwegian Seas region transfers the gas and its compounds from the surface to the deeper waters and sediments. The formation of North Atlantic deep water is believed to be an important mode of transport of carbon from surface waters, since there is a net transfer of CO_2 from the atmosphere to the ocean in the Norwegian and Greenland Seas. This buffering of atmospheric increases of CO_2 is a significant climatic effect in polar regions, but we still do not have an adequate understanding of the processes and rates involved.

The way in which such problems can be resolved is through modeling: identification of processes, and use of basic physical laws to determine their consequences. Our models are not yet sophisticated enough to predict whether positive or negative feedbacks will dominate as radiatively active gases increase in the atmosphere. However, with new measurements that define the processes, and with new, more powerful computers, we have the tools to find out how such problems can indeed be solved.

Climate Processes Study Programs

There have been many scientific programs in the past decades aimed at understanding the role of the polar regions in climate. Notable among these in the late 1970s were the Polar Sub-Program and the POLEX experiment sponsored by the Global Atmospheric Research Program (GARP). These provided calibration and ground truth for satellite measurements in polar regions for the GARP Global Weather Experiment and carried out modeling studies and experiments with data buoy arrays in the Arctic to improve models of pack ice dynamics and air/sea/ice interaction. More recently, the International Marginal Ice Zone Experiment (MIZEX) has studied processes near the ice edge in the Greenland and Bering Seas (see page 66). Continuing buoy measurements in a number of different areas have been carried on by a number of countries. New satellite techniques for imaging ice floes and measuring the total ice cover have demonstrated that we can now collect long-term data sets that will be invaluable for understanding arctic climate processes.

Building on these and other studies, the Arctic Ocean Sciences Board, an intergovernmental group, has sponsored the planning of a Greenland Sea Project to more fully understand the regional mechanisms of air/sea/ice interaction, and to tie seasonal and interannual sea-ice variations to the large-scale dynamics of the atmosphere and ocean in the Greenland Sea region.

The Greenland Sea is particularly good for such studies because the signals are large, there is a good existing data base, logistic accessibility is good, and there is much international interest. Major elements of the program will include data buoys in the ice, acoustic tomography in the ocean (see *Oceanus*, Vol. 25, No. 2, p. 12), hydrography and chemistry, surface and deep floats, and heavy use of satellite measurements. Major contributions are expected to come from the United States, France, West Germany, Norway, Canada, Denmark, and Iceland. The Greenland Sea project is expected to start in 1987 and continue for at least 5 years.

New satellite programs will provide data for the Greenland Sea Project and others, such as MIZEX. These programs, sponsored by the United States, the European Space Agency, and Canada, will provide imaging radars, passive microwave measurements for total ice and snow cover, and cloud measurements in the polar regions.

D. James Baker is President of Joint Oceanographic Institutions, Inc., in Washington, D.C., and Co-Chairman of the Science Planning Group for the Greenland Sea Project of the Intergovernmental Arctic Ocean Sciences Board.

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Arctic Icebreakers:

Soviet icebreaker Dikson, *showing broken ice in its wake. (Courtesy of author)*

U.S., Canadian, and Soviet

by Lawson W. Brigham

Few Americans have ever seen a polar icebreaker. These sturdy vessels operate at latitudes far removed from the temperate regions where most of the United States lies. But the United States is an Arctic nation, thanks to Alaska. And, as many articles in this issue make clear, the United States has a number of vital national security concerns in the Arctic. Addressing many of these concerns will require an increasing U.S. presence in the Arctic, and will result in a steady increase in the volume of marine transportation through the Arctic. In turn, these changes in arctic politics and transportation imply a continuing need for polar icebreakers.

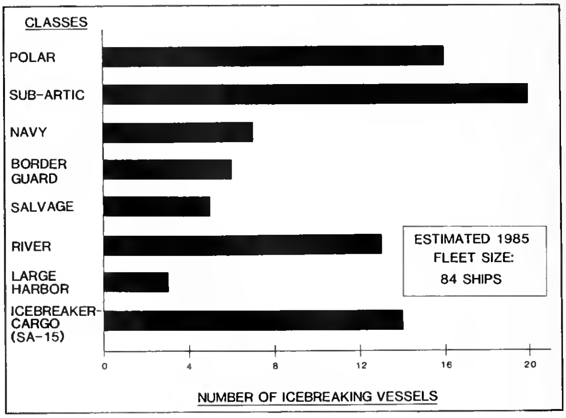
For other Arctic-rim nations, the need is even clearer. The Soviet Union has employed a vast armada of icebreaking vessels along the Northern Sea Route in its concerted effort to develop its northern lands. This route connects Soviet European ports to ports on the Pacific coast via the arctic waters of the Soviet Union. The infrastructure developed to support this marine transportation system—including ice forecasting, remote sensing, pilotage and port development—is an unprecedented polar achievement.

In the Canadian Arctic, commercial icebreaking vessels of a unique design are assisting in hydrocarborn exploration in the Beaufort Sea. A Canadian icebreaking cargo vessel, the *M/V Arctic*, has plied to northern mines for seven years, and Canadian Coast Guard icebreakers work both resupplying arctic communities and supporting commercial traffic through ice-covered waters. Canada also faces jurisdictional disputes that may give impetus to the development of further icebreaking capabilities.

All in all, icebreakers already are of vital importance in the Arctic, and their importance is likely to grow along with the region's population and economic development. Steady improvements in icebreaking technology and capability allow operations in arctic seas once deemed physically impenetrable, and a host of research vessels from many nations now operate in the marginal ice zones of the Arctic.

Soviet Arctic Operations

The Soviet Union operates 16 of the world's 34 polar icebreakers active in the Arctic Ocean. Four of these ships are nuclear powered (the fourth, *Rossiya*, became operational in late 1985). The remaining ships* were built by the Finnish shipbuilder Wartsila from 1959 to 1981 with diesel electric propulsion plants. The Soviet Navy and KGB Maritime Border Guard operate small polar icebreakers. In addition, two classes of river icebreakers with 3.3 and 2.5 meter drafts are specifically designed for the shallow rivers and estuaries of the north. The 14 ships of the SA-15 or *Noril'sk* class of icebreaking cargo vessel also represent a credible icebreaking capability in their own right; they can break continuous level ice up to 1 meter thick.



Soviet icebreaking fleet.

The Northern Sea Route can be defined as the system of marine routes from the Barents and Kara Seas to the Bering Strait in the east. Major icebreaking operations occur in the Kara Sea where ice-strengthened freighters make port calls along the Yamal Peninsula, and in the Ob and Yenisey estuaries. During the past seven years, year-round traffic to the city of Dudinka on the Yenisey River has been accomplished except for periods of breakup when river ice is flushed out during the late spring. Freighters and icebreakers homeported in the Pacific annually resupply communities in the eastern regions of Siberia. Most of the freighters deliver food, fuel, manufactured goods and heavy equipment. Returning they usually carry timber and minerals (copper and nickel). The largest nuclear and diesel-electric icebreakers escort convoys across the route and often are required to "tow" vessels in their V-shaped stern notches.

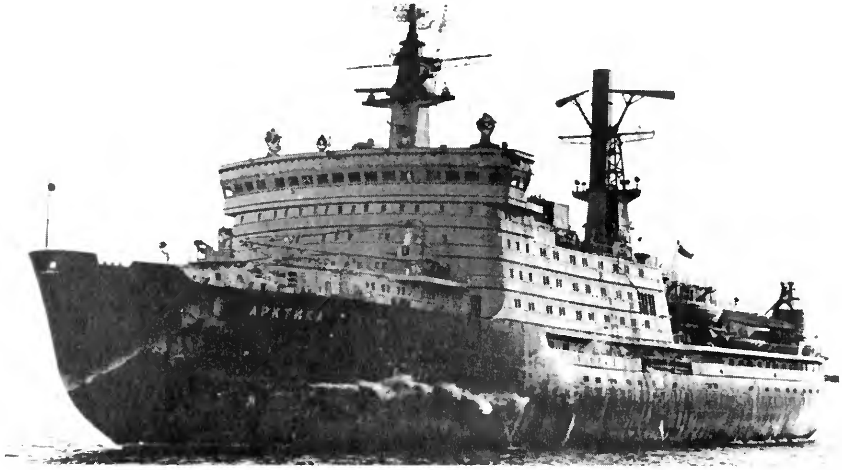
River icebreakers move tug and barge trains inland from the coast. A new nuclear-powered LASH* ship under construction, the *Sevmorput*, will carry 74 barges or more than 1,300 containers, and will be virtually independent of port facilities—a critical feature for work in Siberia. Two new nuclear, shallow-draft icebreakers of the *Taymyr* class to be built by Wartsila will add to the endurance and capability of Soviet icebreakers in continental shelf areas.

This marine transportation system requires extensive technical support. Continuous hydrographic surveys, a modern aids to navigation system, and a host of polar weather and ice information stations provide information necessary for piloting and navigation. Short (hourly, daily), long-range (seasonal, 5-8 months) and ultra long-range (climatic, decades) ice forecasts are published. In

* 3 *Ermak* class (36,000 horsepower and a crew of 150), 5 *Moskva* class (22,000 horsepower and a crew of 145), and 4 *Kapitan Sorokin* class (22,000 horsepower and a crew of 85-92).

* LASH stands for Lighter Aboard Ship, in this case referring to flat-bottomed barges known as lighters. Materials transported to ports by barges can be loaded aboard a LASH ship while still in the same barges, and, at the destination, can be unloaded and once again transported by barge.

Soviet Icebreakers



The Arktika, *since renamed the* Leonid Brezhnev *became the only surface vessel to reach the North Pole in August, 1977. This nuclear-powered vessel and her sister ships are the world's most powerful icebreakers. (Courtesy of author)*

Above, an icebreaker of the Kapitan Sorokin *class. These shallow draft ships are designed for shallow areas along the continental shelf, where deep-draft icebreakers cannot operate. Below, an artist's rendering of a new nuclear-powered, shallow draft icebreaker being built for the Soviet Union by the Finnish shipbuilder Wartsila. It will be among the world's most capable icebreakers. (Photo and painting courtesy of Wartsila)*

A Soviet SA-15 class cargo vessel, capable of continuously breaking 1 meter ice without additional icebreaker support. (Photo courtesy of Wartsila)

Profile of the Sevmorput, *the world's first nuclear-powered, icebreaking LASH vessel. When launched in 1986 it will be capable of carrying 74 barges or more than 1,300 containers, while breaking 1 meter of level ice. After being lifted from the ship by a gantry system the barges will be pushed by tugs along the shallow rivers and estuaries of the Soviet far north. (Courtesy of author)*

Soviet Arctic Marine Transportation Research

Soviet arctic research in marine transportation has been extensive during the past three decades. The development of an experimental ice tank for ship research in 1955 and a nuclear-powered surface vessel (the icebreaker Lenin*) in 1959, both the first of their kind, and the construction and use of the world's most powerful polar icebreakers top the list of Soviet achievements. In addition, the Soviets have set up a complex ice forecasting service, undertaken expansive port development in extreme environments, and produced specialized icebreakers to service the shallow shelves and rivers of Siberia. Additionally, they have established year-round navigation across the Kara Sea to Dudinka, a city on the Yenisey River.*

Soviet research also has emphasized exploration of potential sea routes across the Arctic Basin. The nuclear-powered icebreakers Arktika *and* Sibir *each conducted a highly successful experimental voyage in the 1970s. In August 1977, the* Arktika *made a 14 day trip from Murmansk to the North Pole and back, becoming the first surface vessel to reach that destination. The ship first sailed eastward, across the Barents and Kara Seas, to the Laptev Sea, from which it headed to the Pole, before returning to Murmansk. Although slowed at times to 2 knots, the ship was never stopped by ice. It averaged 11.5 knots during the 3,852 nautical mile journey.*

The following year, the Sibir *escorted the freighter* Kapitan Myshevskiy *across an Arctic Basin route north of the island groups off the Soviet coast. This high latitude voyage from Murmansk to the Chukchi Sea took place during late May and early June, a time when winter ice conditions still prevail in the Arctic.*

A variety of organizations conduct arctic navigation research in the Soviet Union. Leningrad's Arctic and Antarctic Research Institute has more than 500 polar researchers today. Established in 1920, it is considered the leader of Soviet arctic research. At least nine other institutions in Leningrad contribute to arctic marine transportation research, making that city the homebase for such endeavors.

The State Scientific Research Institute for the Design and Planning of Sea Transportation, and the State University are leading centers for arctic transportation research in Moscow. Studies are also conducted at universities and institutes throughout the country, including sites in Gorki, Novorossiysk, Odessa, Murmansk, Vladivostok, Baku, Sochi, and Riga. **—LWB**

September 1983 the Soviets launched a *Kosmos-1500* satellite with a side-looking radar that can provide imagery covering 450 kilometer swaths of the earth's surface. These radar images have improved Soviet ice navigation; they reportedly show multi-year ice edge locations, open water, and various forms of first-year ice.

Despite this intensive operational support, however, in October 1983 a 50-ship Soviet convoy was trapped in difficult ice in the eastern Arctic. Northerly winds brought a drop in temperatures, aided ice formation along the shore two weeks early, and forced multi-year ice into the region. The early freeze-up and persistent northerly winds caused a shipping crisis that required an unprecedented icebreaking rescue operation. More than 3,000 Soviet mariners aboard icebreakers and the merchant vessels were involved. Thirteen Soviet icebreakers including three nuclear ships (*Lenin, Leonid Brezhnev* and *Sibir*, were required to extract the convoy, which was attempting to deliver fuel, building materials, and food supplies to eastern Siberian ports. One freighter, *Nina Sagaydak*, was crushed and sunk by the ice, without loss of life. A second ship was badly holed and more than 30 ships suffered damage during the operation. It was not until late November 1983 that the crisis was resolved. This unusual struggle received wide coverage in the Soviet and Western press, and points out the difficulties of working in the Arctic despite the high level of sophistication of Soviet operations and the arctic experience of Soviet mariners.

Canadian Arctic Operations

In the Canadian Beaufort Sea, commercial operations in support of exploration and development of energy resources have given rise to the evolution of unique icebreakers that are primarily offshore support vessels. Two ships are operated by Canmar Marine Drilling, Ltd. (*Kigoriak* and *Robert Lemur*) and four are owned by BeauDril of Gulf Canada Resources, Inc. (*Terry Fox, Kavlik, Miscaroo* and *Ikaluk*). Fully automated systems allow for small crews—16 to 20 people. Both fleets were designed in Canada and all have direct-drive diesel machinery. Canmar's *Kigoriak*, the first of the ships, was delivered in 1979. Each of the ships reportedly can make steady progress while icebreaking in 1 meter of level ice. Figure 4 shows a typical mission profile of these unique, working icebreakers.

The Canadian Coast Guard provides direct support (ice escort) to commercial shipping during the summer. A fleet of six polar icebreakers* and several smaller sub-arctic icebreakers are deployed north of the Arctic Circle. Early in the 1985 ice season, the majority of icebreaking operations took

* *Louis S. St. Laurent, John A. MacDonald, Pierre Radisson, Sir John Franklin, Des Groseilliers,* and *Norman McLeod Rogers* (crew sizes range from 57 to 80).

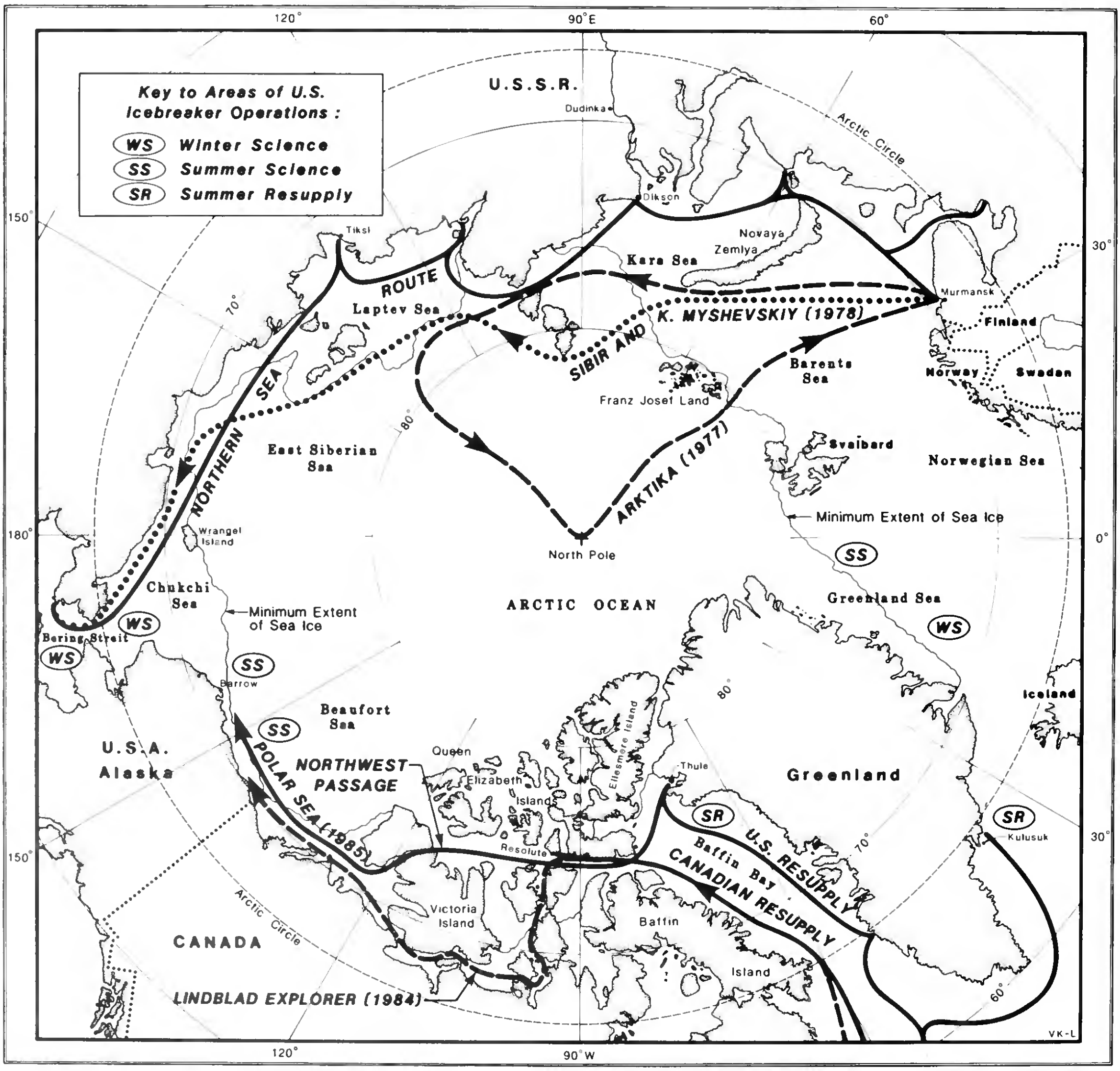
Canadian Icebreakers

The commercial icebreaker Ikaluk *tows a drilling unit through ice off Deadhorse, Alaska, on its way to the Canadian Beaufort Sea. (Photo courtesy of Gulf Canada Resources, Inc.)*

The Robert Lemeur *has water jets to lubricate the hull and improve icebreaking efficiency. This ship is used primarily for support of oil drilling operations in the Canadian Arctic. (Photo courtesy of Canadian Marine Drilling)*

The Canadian Coast Guard icebreaker John A. MacDonald, *only seemingly stuck in the ice. (Photo courtesy of Canadian Coast Guard Northern)* place in Hudson Strait and Lancaster Sound. Other duties for the polar icebreakers included support to aids to navigation (seasonal reactivation), resupply of federal outposts, survey work and scientific research, ice escort of hydrographic vessels, and assist to small tankers refueling communities. Since the early 1970s, following the voyages of the tanker *Manhattan* through the Northwest Passage, the Canadian Coast Guard has had designed several large polar icebreakers capable of operating year-round in most areas of the Canadian north. The initial *Polar 7* icebreaker design (capable of continuously breaking 7 feet of level ice) evolved into a nuclear-powered *Polar 10* design, which was finally downgraded to the present non-nuclear *Polar 8* design. If this ship is built it will be the world's largest and most powerful icebreaker (100,000 horsepower versus 75,000 for the Soviet *Arktika* class). Such a ship with a crew of 116, would allow Canada to exercise year-round sovereignty and jurisdiction in most areas of the Canadian archipelago. It would also support commercial shipping in the Canadian Arctic during the winter season between November and June. The August 1985 transit of the Northwest Passage by the U.S. Coast Guard icebreaker *Polar Sea* has given renewed impetus to the building of this massive ship.

For the past seven years, a Canadian icebreaking cargo ship, the *M/V Arctic* (209-meter length and 29,000 tons), has plied the Canadian Arctic. A joint federal-industry consortium operates the vessel, principally to the Polaris and Nanisivik metal mines. Operational only during the summer months, the *M/V Arctic* has made runs from the Arctic to European ports. Improvements to the icebreaking bow have recently been approved, and it is hoped the navigation season of the ship can be extended to make it more economic in the mining trade.



Map of pioneering voyages and regularly traveled routes in the Arctic.

Definitions of Ships Operating on Ice-covered Waters

- *Ice Strengthened—Vessel able to operate in very open pack ice (less than 3/10 concentration) and first-year ice less than 50 centimeters thick; ship structurally strengthened around the waterline with a conventional or non-icebreaking bow form; safe navigation possible only under escort by an icebreaker.*
- *Ice-capable—Vessel able to operate in first-year pack ice up to 8/10 concentration and 1 meter thick; ship structurally strengthened around the waterline, has an icebreaking bow and has more horsepower than required for transit through ice-free waters; usually designed with adequate power to break continuously 30 centimeters of first-year level ice.*
- *Polar Research Vessel—An ice-capable vessel specifically designed for and dedicated to research; areas of operations include the marginal ice zone and unconsolidated pack ice of the summer melt season; most ships can continuously break up to 50 centimeters of first-year level ice.*
- *Polar Icebreaker—Vessel designed specifically to operate independently in the polar regions in both first-year and multi-year ice; ship structurally strengthened throughout, has an icebreaking bow and has greatly increased horsepower and displacement for continuous icebreaking in 10/10 concentration; polar icebreakers can continuously break a range of ice thicknesses between 1 and 2.5 meters; the estimated world fleet in 1985 is 34 ships.*
- *Subarctic Icebreaker—Vessel designed for icebreaking operations on seasonally ice-covered coastal seas and lakes; ship structurally strengthened around the waterline, has an icebreaking bow and can operate in areas of first-year ice up to 1.5 meters thick; areas of operations include the Great Lakes, Baltic Sea, and coastal regions of Canada, Alaska, and the USSR.*
- *Polar Research Icebreaker—Vessel that incorporates the ice capabilities of a polar icebreaker and the science capabilities of a polar research vessel; has extensive facilities to support oceanographic, meteorological and ice research in the Arctic and Antarctic; capable of continuously breaking a minimum of 1 meter level ice; West Germany's* Polarstern *is the sole example.*

U.S. Arctic Operations

The U.S. polar icebreaker fleet is operated by the Coast Guard (Table 1). Since 1967, there has been a net loss of three ships to the fleet, but the *Polar* class icebreakers have significantly more icebreaking capability than the *Wind* class ships they replaced. Note should be taken of the length of service of *Glacier, Westwind,* and *Northwind.* The two *Wind*-class ships served during World War II in polar waters and are the world's oldest polar icebreakers in continuous service. *Glacier* was completed in 1955 for the Navy and was immediately sent south to Antarctica to serve as Admiral Byrd's flagship. The design is essentially a scaled-up version of the *Wind* class vessels with greatly expanded space for scientific work. For thirty years *Glacier* has faithfully conducted a myriad of scientific and icebreaking operations at both ends of the globe.

Polar Star and *Polar Sea*, the world's most powerful non-nuclear polar icebreakers, have recently confined their arctic operations to the Bering, Chukchi, and Beaufort Seas. Marine transportation studies and oceanographic research conducted primarily for the Department of Defense (Navy)* have occupied most deployments. However, in early summer 1985 *Polar Sea* ventured into the Atlantic via the Panama Canal to the west coast of Greenland for ice escort duties. On 1 August the ship departed Thule, Greenland, enroute the Northwest Passage on a transit that would end in Prudhoe Bay, Alaska, on 12 August.

On reaching Alaskan waters, *Polar Sea* immediately ventured into the Beaufort Sea for defense-related oceanographic research. The political and legal issues of the transit were unique

* Primarily physical oceanography and acoustical surveys.

Table 1. Current United States polar icebreaker fleet.[a]

Name	Homeport	Commissioning Date	Length (m)	Beam (m)	Draft (m)	Displacement (m. tons)	Power[d] Plant	Shaft Power (kW/hp)	Icebreaking[e] Capability (m)
Polar Star	Seattle, WA	1976	121.6	25.5	9.4	12,890	GT	44,742/60,000	1.83
Polar Sea		1978					DE	13,423/18,000	
Glacier[b]	Portland, OR	1955	94.5	22.6	8.7	8816	DE	15,660/21,000	1.1
Westwind[c]	Mobile, AL	1944	82	19.4	8.7	6390	DE	7457/10,000	.9
Northwind	Wilmington, NC	1945							

[a] All icebreakers presently operated by the U.S. Coast Guard.
[b] Operated by the U.S. Navy 1955–66.
[c] Operated by the Soviet Union 1944–52.
[d] Power Plants: GT = Gas Turbine; DE = Diesel Electric
[e] Estimated continuous, level icebreaking capability at 3 knots.

and complex. Canada has claimed sovereignty over all the waters that separate the arctic islands including the route of the *Polar Sea* through Lancaster and Viscount Melville Sounds. The United States has consistently insisted that the Northwest Passage is an international strait through which ships of any country have the right to pass unchallenged and unrestricted. Although the fundamental differences between Canada and the U.S. remain unresolved, bilateral talks on the subject are continuing.

The annual resupply of Greenland bases—Thule and Sondrestrom air bases and the Dye-4 radar site at Kulusuk on Greenland's east coast—have required icebreaker support since 1954. Sealift of dry cargo and fuel is accomplished by Military Sealift Command and Canadian merchant vessels. Although they are ice-strengthened, these ships require icebreaker escort through the sea ice in Northern Baffin Bay and along Greenland's east coast. Except for 1985, *Wind*-class icebreakers have conducted this operation and have also conducted extensive oceanographic surveys along Greenland's northwest coast (Baffin Bay, Smith Sound, Nares Strait and Kane Basin). In recent years the ships have deployed in the Greenland and Norwegian Seas for lengthy oceanographic surveys. Winter science operations have been conducted in the Bering and Chukchi Seas by both *Wind* and *Polar* class vessels. *Glacier* has deployed occasionally to the Alaskan Arctic for marine geological and ecological investigations.

National Need for a Polar Fleet

The U.S. polar icebreaker fleet, operated jointly in the past by the Coast Guard and Navy and today solely by the Coast Guard, has played an instrumental role in building and supporting our national presence in both polar regions.

The primary tasks of the fleet are to conduct a wide variety of national strategic and scientific missions in polar marine environments. First, the fleet represents an instrument by which policy-makers can promote essential U.S. security interests and provide a credible and influential maritime presence in the Arctic and Antarctic. This "active and influential" role by icebreakers in the Arctic is best exemplified by the voyage of the Soviet Union's *Arktika* to the North Pole in 1977. Although other forms of polar presence are possible, the multi-mission Coast Guard polar icebreakers can provide the President with flexibility, operational reach, and staying power in the polar regions, particularly if an urgent need arises. Other polar operations of a strategic nature are conducting Antarctic Treaty inspections, projection of U.S. presence into international polar waters, conduct of defense-related research, responding to foreign ship intrusions into Alaskan waters, and providing support to military operations.

Ice escort and logistic support have been primary missions since the fleet's inception during World War II. More than 45 percent of the fleets' time has involved these two, key missions. The resupply of McMurdo Station in Antarctica, of Thule and Sondrestrom air bases along Greenland's west coast, and of the desolate East Greenland radar site in Kulusuk require polar icebreaker escort of ice-strengthened ships. These operations have been coordinated by the Military Sealift Command. Icebreakers have been involved in cable-laying operations in Baffin Bay, ice escort of the research vessel *Glomar Challenger* in polar waters, and resupply efforts throughout the American and Canadian Arctic. They also have been used extensively as bases of operation in support of submersibles, ice islands, and aids to navigation projects.

A fourth primary mission that has accounted for almost half the polar icebreaker employment days in both the Arctic and Antarctic is support to scientific operations as a platform for observation. Marine science investigations have covered the full spectrum of disciplines. Many of the Arctic oceanographic cruises during the 1960s and 1970s aboard polar icebreakers gathered the only bathymetric and acoustical data bases for these regions, especially in the Greenland, Barents, and Kara Seas.

Another research-related mission has been the use of polar icebreakers as sensor platforms for instruments that measure engineering parameters associated with icebreaking. Marine transportation tests in Alaskan waters, full-scale icebreaking tests, and various acoustic systems studies have advanced the design of polar vessels. This research is conducted primarily in anticipation of the need for a polar transportation capability in the next century. Such a polar transportation system around Alaska's coastline would also require an increased federal presence in the form of icebreakers to conduct the statutory missions of the Coast Guard. Offshore development of the Alaskan Arctic would lead to requirements for enhanced Coast Guard response in environmental protection, marine safety, search and rescue, and enforcement of laws and treaties—all on ice-covered waters.

Polar Icebreaker Requirements Study

In 1983–84 an interagency committee in Washington attempted to assess future U.S. requirements for polar icebreakers. The study group included representatives of the Coast Guard, Marad, DOD, NSF, NOAA, OMB and OST*. The study was to assess the national need for a polar icebreaker fleet, recommend a fleet size to meet all requirements to the year 2000, and to develop financing options for the construction and operation of the fleet. Comprehensive analyses were performed on the status of the present fleet and alternatives to a federal polar icebreaker fleet. A survey of users was conducted to ascertain peacetime and wartime requirements. After nearly a year of discussion and debate an interagency report entitled *United States*

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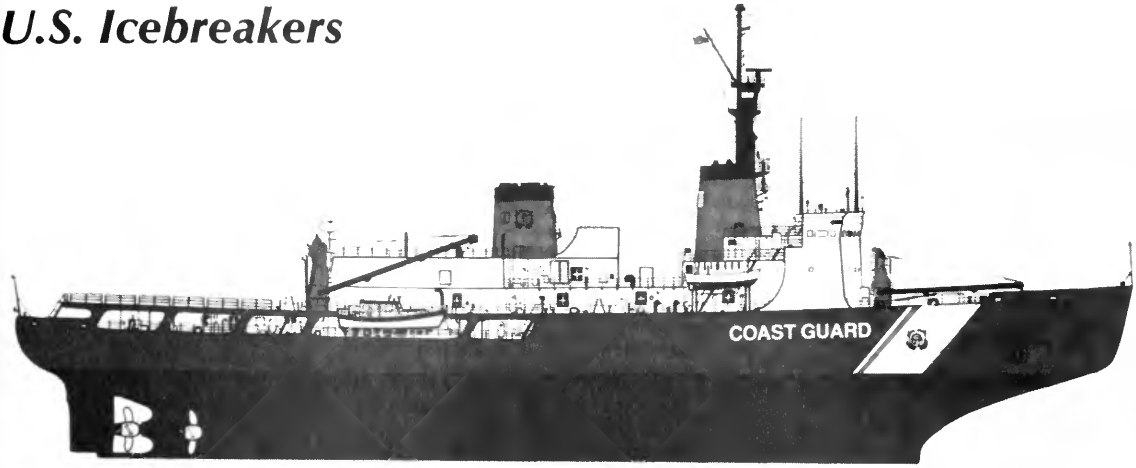
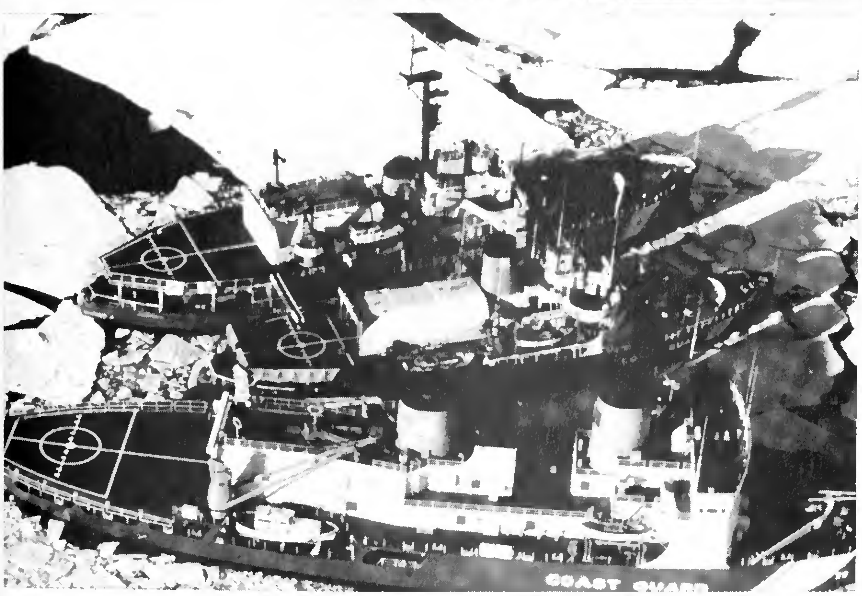
* Marad: Maritime Administration; DOD: Department of Defense represented by the Oceanographer of the Navy; NSF: National Science Foundation; NOAA: National Oceanic & Atmospheric Administration; OMB: Office of Management & Budget; OST: Office of the Secretary of Transportation.

U.S. Icebreakers



The U.S. icebreakers Polar Star *and* Polar Sea *are the most powerful Western icebreakers. Shown at right is the* Polar Sea. *Above, note the hull configuration of an icebreaker. (Photo and drawing courtesy of U.S. Coast Guard)*



All three classes of U.S. icebreakers, together for a moment off Antarctica—the Glacier *(top),* Northwind *(middle), and* Polar Sea. *(Photo courtesy of U.S. Coast Guard)*

Polar Icebreaker Requirements Study was published in July 1984. Several of the principal findings are:

- *The polar icebreaker fleet is essential to the national interest.*
- *The fleet should be operated by the Coast Guard.*
- *Capital costs of replacement icebreakers should be funded by a single agency, the Coast Guard.*
- *Improvements in the present fleet are necessary, specifically in capability to support science.*
- *A fleet of 4 ships should be maintained; the Coast Guard recommended a fifth ship remain in reserve for emergencies or possible increases in difficult-to-forecast, long-term polar requirements.*
- *Work should be started immediately on the design of a new polar icebreaker; design of the new icebreakers should enhance science support while retaining essential escort and logistical capabilities.*
- *The Coast Guard should design upcoming replacements with an icebreaking capability between the present* Wind *and* Polar *class vessels.*

Soon after completion of the study two Congressional Acts contained language that emphasized the polar icebreaker fleet. The Arctic Research and Policy Act of 1984 called for the Office of Management and Budget to facilitate planning for the procurement and operation of polar icebreakers for arctic research. In addition, Congress, in the Coast Guard's Authorization Act of 1984, has mandated that the Secretary of Transportation prepare design and construction plans for the purchase of at "least two new polar icebreaking vessels." Thus, the stage has been set for replacement of America's aging polar icebreaker fleet.

Required Capabilities

While it is premature to discuss specific characteristics prior to any budget decisions, important capabilities for the new U.S. icebreakers are readily apparent. New polar icebreakers must be multi-mission in design and be capable of operating independently in both polar regions.* The ability to operate effectively during Arctic and Antarctic polar winters will be a significant design feature since scientific operations in the coming decades are likely to be conducted in those extreme seasons. The ships must possess an icebreaking capability to penetrate the continental shelves of Antarctica and operate in the northerly reaches of the Beaufort and Greenland Seas. Enhanced remote sensing imagery will be mandatory for improved ice navigation, particularly for increased operations that are likely to occur in multi-year ice. The receipt, processing, and display of real-time satellite and aircraft ice imagery will be critical to future scientific investigations, as well as other missions.

There is no doubt that the new U.S. icebreakers must be designed with greatly enhanced scientific capabilities. In fact, the new design should approach that of a polar research icebreaker—a ship similar in science capability to West Germany's *Polarstern*, but with increased icebreaking capability. Examples of potential science support features of the replacement polar icebreakers include:

- *Ability to conduct hydrographic and bathymetric (broad beam) surveys in all seasons.*
- *Extensive cold storage and cold rooms.*

Quotes from Three Documents Concerning U.S. Polar Icebreakers

The Office of Management and Budget shall seek to facilitate planning for the design, procurement, maintenance, deployment, and operations of icebreakers needed to provide a platform for arctic research by allocating all funds necessary to support icebreaking operations, except for recurring incremental costs associated with specific projects, to the Coast Guard.

—from Section 110.(b.), Arctic Research and Policy Act of 1984

Work should be started immediately on the design of a new polar icebreaker. . . . The design of the new icebreakers should enhance research support, while retaining essential escort and logistic support capabilities.

—from Recommendation 2, U.S. Polar Icebreaker Requirements Study, July 1984

The Secretary of the department in which the Coast Guard is operating shall prepare design and construction plans for the purchase of at least 2 new polar icebreaking vessels to be operational by the conclusion of fiscal year 1990 . . . the Secretary shall consult with other interested Federal agencies for the purpose of ensuring that all appropriate military, scientific, economic, and environmental interests are taken into account.

—from Sec. 6.(b), Coast Guard Authorization Act of 1984

* Nuclear power for polar icebreakers has been proven by the USSR to be safe, reliable, and highly effective. The key to nuclear power is that it provides virtually unlimited endurance in the Arctic Ocean—a region where refueling ports are few and far between. Both the high cost and the extensive infrastructure (training and maintenance) required to support a nuclear ship would probably scuttle any U.S. Coast Guard plan to acquire such a ship. However, it is quite clear that a nuclear-powered polar icebreaker is the most effective surface platform for polar operations.

Marine Transportation Research in the Alaskan Arctic

Since 1979, a program jointly sponsored by both the government and industry has been conducted to assess the operational feasibility of year-round marine transportation in offshore Alaska. The main objectives of these "trafficability" studies have been to:

- *Define the ice and environmental conditions which would affect year-round marine activities in the Bering, Chukchi, and Beaufort Seas.*
- *Evaluate the performance of powerful icebreakers by measuring hull ice loads (continuous and ramming icebreaking), steering gear loads and structural vibrations. The data will be used to improve design criteria for polar ships and offshore structures.*
- *Assess ship piloting and ice navigation abilities and the maneuverability of large vessels in ice.*
- *Demonstrate the operational feasibility of commercial icebreaking ships along arctic marine routes.*

Joint sponsorship and cost-sharing have enabled the expensive program to operate. Among the government participants are the Coast Guard, the National Research Council, and the Maritime Administration. The Alaska Oil and Gas Association, U.S. shipyards, the State of Alaska and Transport Canada also have contributed.

Ten scientific voyages to the Bering, Chukchi, and Beaufort Seas during the last seven years have been conducted aboard the world's most powerful non-nuclear icebreakers, the Polar Star *and the* Polar Sea. *Initial results indicate that the* Polar *class vessels can operate year-round in the Bering Sea. Winter operations in the Chukchi Sea appear possible at this time. Winter transits into the Beaufort Sea, however, do not seem feasible without refueling en route.*

Ice navigation—through the use of remote sensing ice imagery—and ice piloting skills have proven to be vital to the success of any Alaskan marine system. Zones of environmental severity also have been identified for each of the Alaskan seas by using ice imagery and the extensive field data gathered on ice floes, pressure ridges, and rafted ice features.

More than 1,400 sets of data on the impact of both first- and multi-year ice on the hull of the Polar *class icebreakers have been collected. These, along with other data, have helped develop analytic models predicting the performance of ice-transiting ships in level ice and pressure ridges. The success at defining the significant requirements of an arctic marine transportation system is the result of the multi-year nature of the program.* **—LWB**

- *State of the art computer systems for onboard processing of data and the capability to transmit large amounts of data to home base.*
- *Heavy lift capability to handle moored instrument arrays and other large packages.*
- *Coring and dredging capability.*
- *Ability to conduct acoustic surveys and tow arrays.*
- *Specialized labs in vans (containers) that are compatible with the UNOLS* fleet.*
- *Temperature controlled wet and dry labs with uncontaminated seawater.*
- *Precision navigation (Global Positioning System) and satellite communications.*
- *Easy access to the ice surface by scientists and equipment.*
- *Full monitoring of the ship's operations by video and ship's data displayed throughout all scientific spaces.*
- *Independent electronics lab for repair of computer and scientific equipment.*

* University National Oceanographic Laboratory System: This consortium of oceanographic research organizations manages the deployment of U.S. Oceanographic research vessels.

The Future

The tempo of icebreaker operations throughout the Arctic Basin probably will continue to increase well into the next century. Offshore exploration and development of the Soviet and North American Arctic will increase the importance of polar icebreakers to marine transportation, offshore operations, and scientific research.

The Soviet Union will continue its heavy investment in the marine transportation system established along the northern sea route. Development of nuclear-powered, shallow-draft icebreakers of the *Taymyr* class and the nuclear LASH ship *Sevmorput* provide glimpses of the Soviet effort. There is little doubt that there is a trend toward icebreaking cargo ships operating independent of icebreaker escort in the western part of the Soviet Arctic. However, polar icebreakers will continue the practice of convoying in an attempt during the next two decades to establish an effective, year-round navigation season across the entire length of the Soviet north. Commensurate with this effort will be a continued investment in remote sensing of ice conditions and extensive scientific research aimed at both the economic and strategic polar interests of the Soviet Union. A wide variety of Soviet icebreaking vessels, particularly those designed for geophysical and oceanographic work, will participate in this effort, concentrating their operations on the continental shelf.

In Canada, the federal government will in all likelihood proceed with the construction of the world's most powerful icebreaker, the massive *Polar 8*. Such a ship will be designed to "guard" Canadian Arctic sovereignty and will be expected to operate year-round in all but the most difficult ice regions of the Canadian north. Additional *Radisson* class icebreakers will be added to replace aging Canadian Coast Guard ships used during seasonal resupply efforts and for support of Arctic commercial vessels. Canada's Arctic shipping experience with an improved *M/V Arctic* that can extend the navigation season could make Arctic mining more competitive in international markets. Steady, but slow, offshore development in the Canadian Arctic is expected and will result in the continued operation of icebreakers and supply vessels uniquely designed for the Beaufort Sea. The result of this activity is that icebreaker operations during the coming decades will reach an all-time high. With the launch in 1991 of Canada's *Radarsat* spacecraft carrying a synthetic aperature radar, real-time ice imagery will be available for ice navigation in Canada's ice-covered waters.

For the United States the future of polar icebreakers is just as clear. The justification for a replacement fleet is linked less to the commercial development of arctic resources, than to a broad spectrum of strategic, scientific, and logistic requirements for a viable, modern fleet. The federal government also will have an increased responsibility to safeguard the public interest in the face of resource development in offshore Alaska. These future responsibilities lend additional impetus to the replacement of the polar fleet. As designs for the new ships advance, the Coast Guard must articulate the appropriate operational and support capabilities to meet the nation's needs in both polar regions. Neither the Coast Guard, Department of Transportation, nor icebreaker user agencies can afford to view these ships parochially—as anything less than *national assets* used for a multitude of functions.

It is interesting to note that more than 30 years ago the U.S. maintained the world's sole multi-mission polar icebreaker fleet. Then as now the fleet operated globally and supported such diverse activities as the establishment of Greenland air bases, the construction of DEW (Distant Early Warning) Line sites across the North American Arctic, Admiral Byrd's and subsequent Antarctic expeditions, and scientific operations in polar seas where vessels had never sailed. In the budget battles that lie ahead, it will be important to reflect on this historic role and to measure the importance of the fleet to the future of U.S. polar science and polar affairs of state.

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The views expressed are solely those of the author and do not necessarily reflect the positions of the U.S. Coast Guard or the Department of Transportation.

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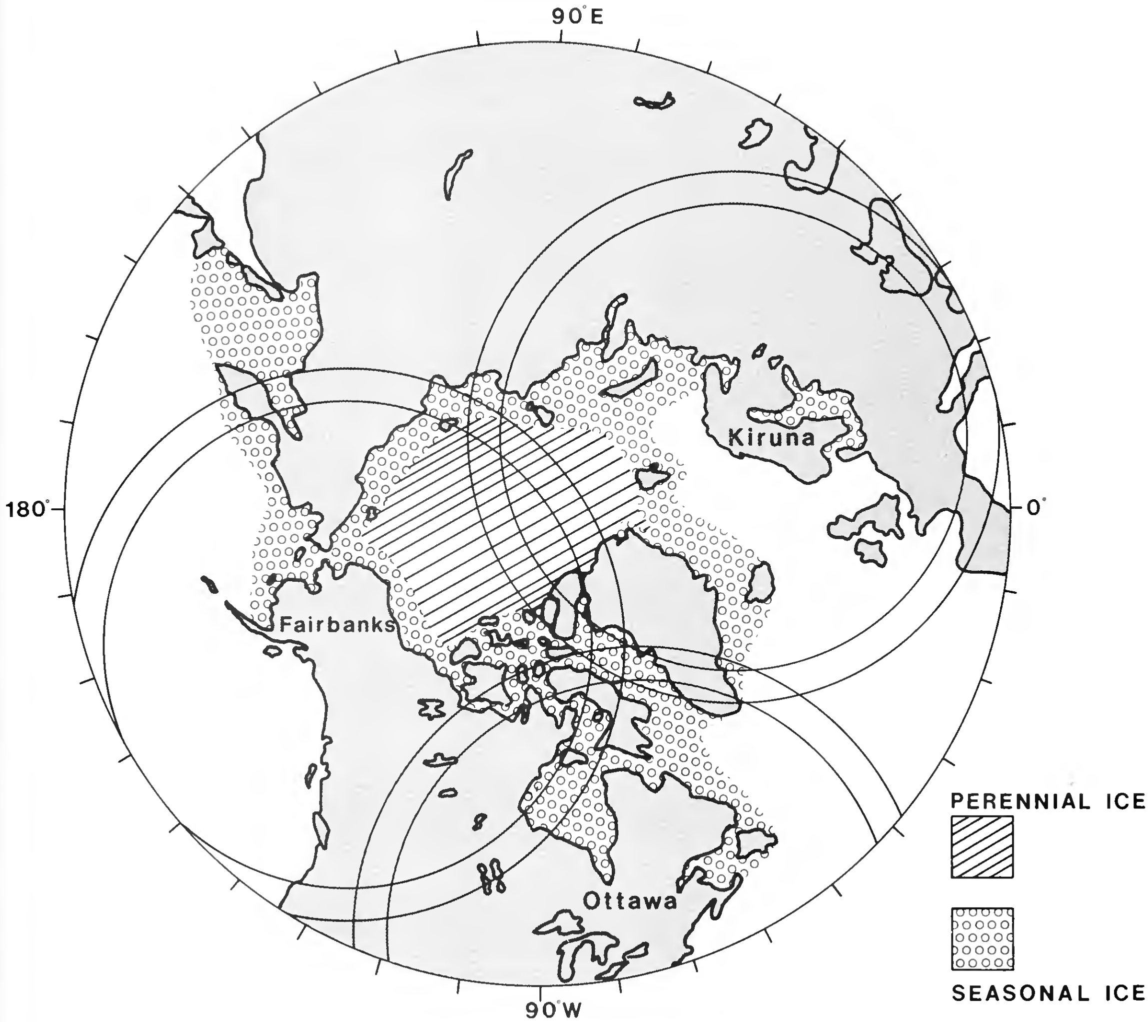

Figure 1. Approximate maximum and minimum extent of sea ice in the northern hemisphere. The circles indicate the receiving areas for the 3 proposed Northern Hemisphere SAR stations. The inner and outer circles give the coverages expected from SAR satellites to be launched by the European Space Agency and the Canadian Centre for Remote Sensing, respectively.

Remote Sensing of the Arctic Seas

by W. F. Weeks and F. D. Carsey

What characteristics of the ice-covered seas of the Arctic would we like to observe? It would not be hard to make a long list. For starters, we would need to know where the ice is, its velocity, the ice type, its thickness, its properties and where the thin ice areas and open leads are located. Because the ice is pushed by the winds and currents, we also will have to know these characteristics as well as the air temperature, the surface radiation balance, the snow cover and the ocean heat flux—factors that influence the rate that ice grows or decays.

We also would like to understand the complex feedback mechanisms that occur as a result of interactions between the atmosphere, the ice, and the ocean. Sounds like a tall order? It is! Particularly when you consider that in the Northern Hemisphere alone, during the period of a maximum ice extent, sea ice covers a region two times the area of the contiguous United States (Figure 1). Included are locations as far south as the Yellow and Okhotsk Seas and the Gulf of St. Lawrence. Even during times of minimum ice extent in the late summer, the total ice-covered area shrinks only by half. During this period, however, the ice is confined to regions that are more conventionally considered as Arctic (that is, the Arctic Ocean, the East Greenland Sea, and the Canadian Archipelago).

Not only is our area of interest very large but the conditions we wish to observe change rapidly with individual ice floes drifting as much as several kilometers a day. This means that frequent, systematic observations are necessary. Observations made at coastal stations are commonly not representative of conditions offshore, and long-term manned surface observations within the ice pack are almost non-existent. The only "continual" manned presences in the whole Arctic Ocean are the one to two Soviet drifting stations. The situation is tailor-made for satellite-based remote sensing. Remote-sensing instruments placed on satellites in polar or near-polar orbits can view the arctic seas at frequent intervals and send their observations back to Earth.

If satellite-based remote sensing can contribute to documenting the behavior of the arctic seas, the observational data base will spur the development of improved models for forecasting environmental conditions in this important, but neglected region. These models also can then be utilized to examine interactions between the arctic seas and the rest of the World Ocean. To attempt to unravel the complex, interconnected processes occurring in the arctic seas without an adequate observational base that covers the whole region is a hopeless task.

There are, however, problems that must be kept in mind. For one, those parts of the arctic seas near the pole experience a prolonged period of darkness during the winter months. In addition, many areas of interest are often shrouded in fog and cloud. This is particularly true of regions in the marginal ice zone (MIZ), near the edge of the pack ice where air/sea/ice interactions are intense. Therefore, to be most useful, satellite sensors should provide information both in the dark and through clouds. These combined constraints limit possible sensors to those that operate in the microwave portion of the electromagnetic spectrum with frequencies roughly ranging from 100 megahertz to 100 gigahertz (wave lengths varying from a few millimeters to just over 1 meter). Sensors operating in this frequency range are of two basically different types: those that passively observe the natural microwave emission from the Earth's surface and those that transmit bursts of microwaves and measure the time of travel of the waves to and from the Earth's surface, as well as the nature of the return. These sensors obtain data sets that are quite different in character.

Passive Microwave Sensors

Passive microwave sensors measure the brightness temperature (T_B) of the Earth's surface with a resolution that increases as wavelength decreases. For representative modern systems, surface resolutions are quite coarse, varying from 12.5 to100 kilometers; hardly adequate for resolving typical sea ice features. Each of the individual T_B values, which are commonly combined to produce a map-like image of the Earth's surface, represents an average of the brightness temperatures of ice areas of different thicknesses and types plus that of any open water areas (leads) that exist within that resolution element.

The term brightness temperature is a bit misleading in that it is not a real temperature but is instead given by the product of the emissivity (ϵ) of the material (sort of a material "constant") times its physical surface temperature: $T_B = \epsilon T_s$. As the value of ϵ for open water is approximately 0.5 as contrasted with values of 0.8 to 0.95 for different ice types, there is a striking T_B difference between the ice-free ocean and consolidated pack ice (differences of more than 100 degrees Kelvin are common).

Therefore, useful maps of the boundaries of the pack ice and of ice concentration (the percent of the sea surface covered by ice) can be prepared from data collected by a single frequency passive microwave system (Figure 2) for cases where only one ice type is present. Unfortunately examples of arctic regions with only one ice type present are uncommon. However, this situation does apply to the ice remaining in the Arctic Basin at the end of summer. The passive microwave record (1973–76) for this region has been analyzed (Figure 3) and provides estimates of the mean emissivity and mean ice concentration.

In agreement with aircraft observations, the heaviest ice is located in a broad band north of Greenland and the Canadian Archipelago. The average volume of ice surviving the summer is estimated to be 16×10^3 cubic kilometers. Currently deployed passive systems, as well as proposed future systems, operate at 4 to 5 frequencies; so it is possible to utilize such systems to estimate the percentages of open water plus that of more than one ice type. Current studies are focused on discriminating multi-year from first-year ice. Although developing and verifying such estimation algorithms might appear to be straightforward, this is far from the case, particularly if estimation errors of a few percent are to be achieved so that the results will be useful in testing model simulations of pack ice behavior.

Active Microwave Sensors

Of the several types of active microwave sensors, imaging radar is particularly well suited for sea ice studies. Synthetic aperture radar (SAR) systems designed for space deployment take advantage of

Figure 2. Ice concentration contours for the Bering Sea on 19 February 1983 based on passive microwave data from the sensor on Nimbus-7 satellite. (MIZEX—West Study Group, 1983).

the orbital motion of the satellite to store and combine information from a number of pulses along the track to synthesize high resolution (20 to 30 meters) observations as if they were obtained via the use of a very large antenna. Data processing is complex and data rates are so high that it is not presently practical to store SAR data onboard the satellite for playback while over a receiving station. Therefore to receive SAR imagery of the Arctic, receiving stations must be located within line-of-sight of the satellite while it is over the Arctic. Present Soviet radar satellites (Kosmos-1500) avoid these problems by using real aperture radar systems; the price paid for this convenience is a loss of resolution from 30 meters to 1 kilometer.

SAR images (Figure 4) contain a wealth of information and allow one to track the movement of individual pressure ridges, leads, and floes under all weather conditions. In addition, surface wind directions can be derived from the orientation of slush streamers, the nature of the ice edge can be examined in great detail, and multiyear and first-year ice can be differentiated. In the open ocean, SAR provides information on swell direction and on internal and surface waves. The interpretation of the imagery from sea ice is generally straightforward with the major factor contributing to the strength of the return being the surface roughness. Therefore, ridges, rubble, and waves give strong returns, while flat ice and calm seas give low returns. In most cases, it is the combination of the strength of the return and its areal pattern that allows for unambiguous interpretations (see *Oceanus*, Vol. 24, No. 3).

Other Sensors

Although we have stressed microwave systems because of their all-weather capabilities and the synergistic nature of their very different observations, the arctic capabilities of other satellite sensor systems also should be noted. For instance, visual and thermal infrared systems provide important meteorological information plus, weather permitting, occasional glimpses of the ice with associated surface temperature measurements. These observations serve as useful aids in interpreting microwave images. Also useful are ocean color imagers which detect variations in the concentration of chlorophyll in surface waters near the ice edge; and scatterometers which provide estimates of wind speed and direction over the open ocean. Laser profilers have been used successfully from aircraft to study the surface roughness of the ice and ocean wave characteristics, but have not to date been deployed in space.

What is missing? Capabilities for ice observations are excellent (Table 1). The most significant gap is the lack of an ability to remotely determine sea ice thickness with good spatial resolution. There appears little chance of a satellite system obtaining such measurements.

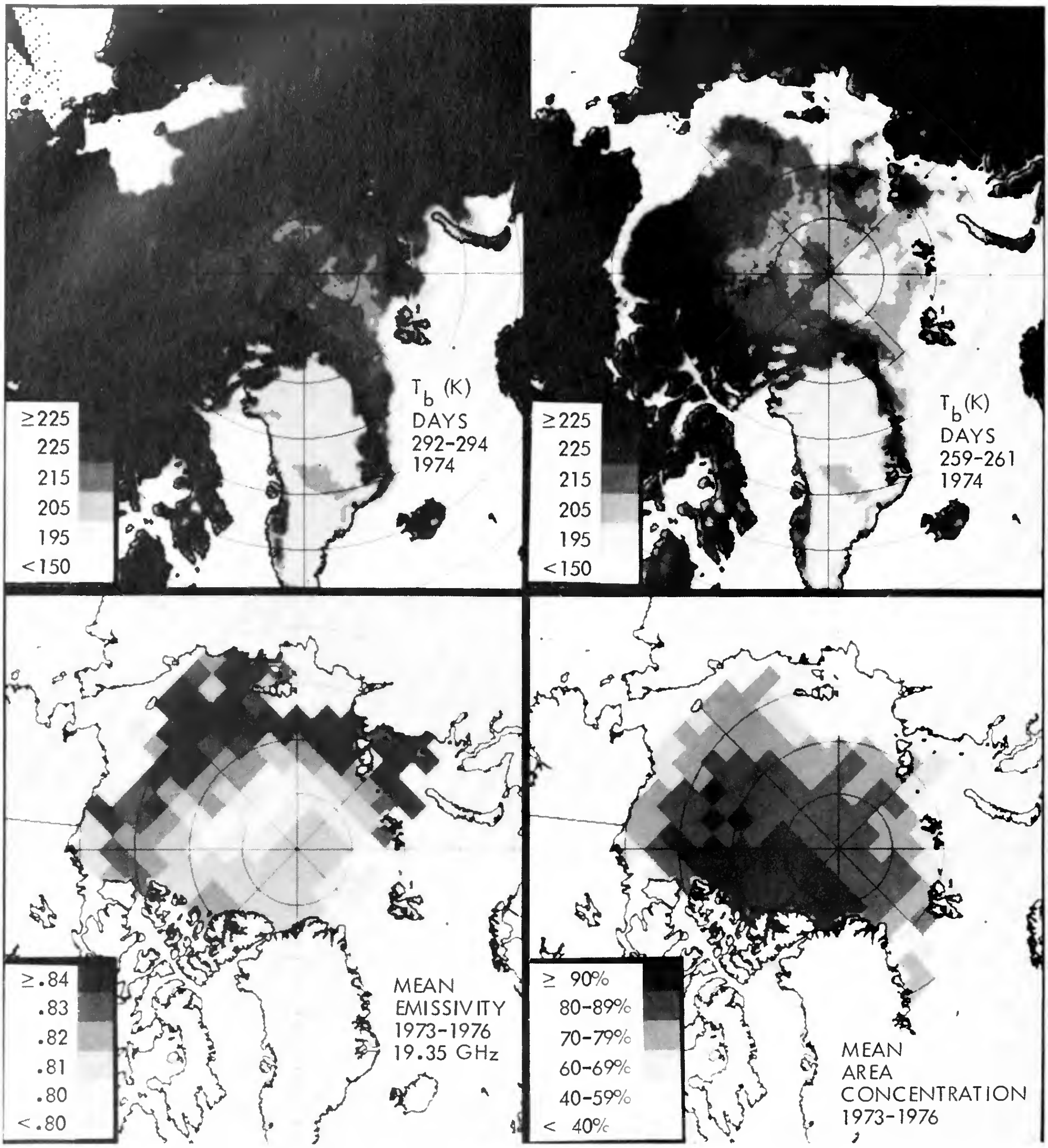

Figure 3. Single channel microwave brightness data from Nimbus 5 at 19.35 GHz analyzed over the summer-fall transition. The upper figures show the measured brightness temperatures in mid-September and late October. The high brightness of the new ice is clearly shown in the Laptev, East Siberia, and Beaufort Seas. The lower figures show the observed mean fall emissivity and the mean areal concentration at seasonal-extent minimum. This same data set showed the extent of ice-covered seas at minimum extent to have very little change in total area, but to occupy different parts of the basin in different years.

Among meteorological parameters, the major data gap results from the ice interferring with existing techniques for estimating wind velocity. In open water, data gaps result from the inability of the electromagnetic radiation at typical remote sensing frequencies to penetrate significant distances into the water column. This problem is made even more difficult by the presence of ice. In order to obtain at least some of this missing information, remote sensing will clearly have to be supplemented by surface observations.

Future Deployments of Sensors

To discuss future instrument deployments in detail

Table 1. Environmental observations required for the arctic seas; plus satellite-borne remote sensing systems capable of providing such information.

Parameter	Remote Sensing System	Comments
ICE		
Extent	passive μ-wave, radar	
Concentration	passive μ-wave, radar	
Type	radar, passive μ-wave	
Velocity	radar	
Thickness	radar, passive μ-wave	indirect information from ice type
Roughness	laser profiler*, radar	* not flown to date
Temperature	IR	
Properties	radar + IR	indirect from ice type and temperature
Snow cover	radar, passive μ-wave	
ATMOSPHERE		
Clouds	visual + IR scanners	
Winds	scatterometer, passive μ-wave	only from ice-free areas
OCEAN		
Chlorophyll	ocean color imager	only from ice-free areas
Waves	radar	open ocean and thin ice areas only
Temperature	IR	surface temperature only
Salinity	none	
Currents	radar-altimeter	only from ice-free areas

requires combining a cascade of acronyms with extensive crystal ball gazing. Showing our erudition by flashing all this past the reader would undoubtedly result in both confusion and sleep. The overall result, however, can be summarized rather simply. As Table 2 shows, if the proposed sensor deployments of NASA, NOAA, the Navy, the European Space Agency (ESA), the Canadian Centre for Remote Sensing (CCRS) and the Japanese Space Agency (NASDA) go reasonably close to schedule, we can expect at least one low-resolution visible and infrared sensor, a high-resolution visible sensor, and a passive microwave sensor to be operational from the present through the forseeable future.

Most important, starting in 1990 there will be 3 SAR satellites launched; one by ESA, one by NASDA, and one by CCRS. This last satellite, called Radarsat, is the "Cadillac" of the set, and is, at long-last, a satellite system designed with ice studies as a primary focus. The lack of a radar altimeter for a few years after 1992 would not appear to be a particularly pressing problem in the polar regions, in that this system is primarily useful in profiling the large glacial ice sheets—entities which are not given to overnight changes.

The most important fact revealed by Table 2 is that from 1990 on both passive microwave and SAR systems will be operating simultaneously over the Arctic. In addition, three SAR receiving and data processing stations will provide arctic coverage. These are located in Fairbanks, Alaska; Ottawa, Canada; and Kiruna, Sweden (Figure 1). With the exception of a small "hole" off the central Siberian Coast, the coverage of the Arctic Seas will be complete, particularly since a SAR receiving station also will be located somewhere in Japan.

Although the times of deployment shown in Table 2 only extend until 1995, it is quite probable that most sensors operating at that time will continue to be effective until 1998 when the NASA Earth Observing System (EOS) [that is, the polar-orbiting component of the Space Station] is expected to become operational. The proposed EOS remote sensing package is varied and powerful and includes multifrequency SAR, passive microwave systems, radar and laser altimeters, a high and a moderate resolution imaging spectrometer, a scatterometer, and an atmosphere sounding package. Clearly EOS will expand environmental observations over the arctic seas. Also included as part of this program is a data system that will greatly facilitate access, transfer, and analysis of the observations by scientists throughout the world.

Data Buoys

As mentioned earlier, certain critical environmental measurements cannot be obtained through satellite-based remote sensing because the presence of ice interferes with certain surface observations and also prevents observation of the underlying ocean. Fortunately, several important missing observations can be obtained by autonomous data buoy packages deployed on the ice, drifting in the ocean, or moored on the seafloor. For instance, since 1979 the Arctic Data Buoy Program has systematically collected observations on atmospheric surface pressure (used to calculate surface winds), temperature, and ice motion.

At present, work is underway to increase the capability of such monitoring systems via the development of so-called "smart" buoys that can accommodate a wide variety of sensors. Further measurements may include direct surface wind velocity observations, upper ocean temperatures and salinities, oceanic heat fluxes, ice and snow thicknesses, and short wave radiation. Also under development are bottom moored buoys that provide information on the mean thickness of the sea ice passing over the buoy. By 1990, development and testing of such systems should be completed and routine operations well underway. By the mid-1990s we also expect to see the deployment of SOFAR (SOund Fixing And Ranging) drifting buoys that

Table 2. Times of deployment of at least one of a given type of sensor for the years 1986 to 1995.

Type of sensor	86	87	88	89	90	91	92	93	94	95
Low resolution visible and IR	—	—	—	—	—	—	—	—	—	—
High resolution visible	—	—	—	—	—	—	—	—	—	—
Ocean color imager	—?							?—	—	—
Radar altimeter	—	—	—	—	—	—	—			
Scatterometer				—	—	—	—	—	—	—
Passive microwave	—	—	—	—	—	—	—	—	—	—
Synthetic aperture radar					—	—	—	—	—	—

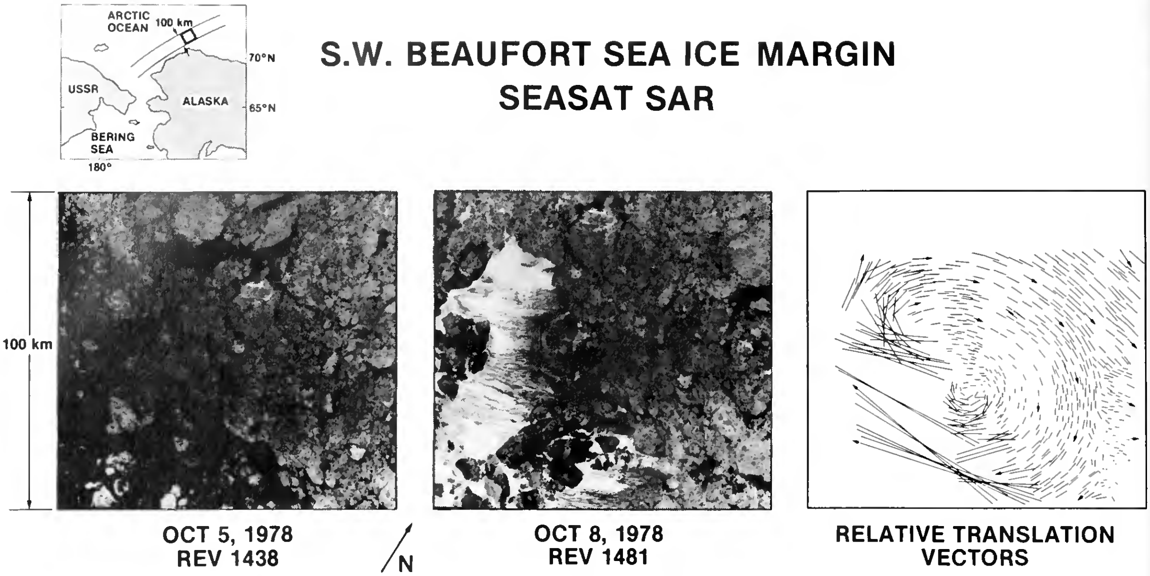

Figure 4. Seasat SAR images of the southwest Beaufort Sea in the fall of 1978. Shown at left and center are two images of the same area taken 3 days apart; at right is the plot of the drift tracks of about 700 features common to both images. A few arrowheads are drawn on the drift tracks to indicate the sense of the motion. In the SAR images, dark areas are new ice; light areas are open water; grey areas textured with lacy white lines are old floes, the lines being ridges and fractures; and the area with fringed appearance in the center image contains ice herded by the wind. The drift tracks clearly show an anti-cyclonic eddy adjacent to and possibly being driven by eastward and northward tending coastal jets. The longest tracks represent an ice speed of about 25 centimeters per second.

freefloat at various depths in the ocean and communicate data back to master stations designed as components of smart buoys. In such systems, the smart buoys serve both as reference locations required to establish the positions of the SOFAR floats and as data transfer systems that pass the information on to satellite data relay stations. With such systems, environmental observations made in the remotest part of the central Arctic Ocean can appear on the computer screen in a scientist's home office within minutes after the field observation is completed.

Exciting Horizons

The next 15 years may be the most exciting period in history for scientists interested in the geophysics of the arctic seas. The satellite and buoy systems we have described are not pie-in-the sky. They either are functioning or are in advanced stages of development. They are not cheap, but neither is the prospect of establishing the 30-manned, drifting stations that would be required to provide reasonable coverage of just the Arctic Ocean.

In addition, rapid advances are being made in formulating fully coupled air/ice/ocean models that incorporate processes operating on a wide variety of time and space scales. As part of these developments, we anticipate the formulation of models that will directly incorporate the satellite and buoy data in a continuing process of resetting current ice/air/ocean conditions and evaluating past forecasts. When this is accomplished, we can more fully investigate the role of the Arctic in affecting world climate.

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Icebreaking Tankers, Cargo Subs, and Hovercraft

Much of arctic development is driven by the search for and exploitation of fossil fuels. A key issue of this modern day gold rush has been how to get these fuels from the Arctic to the regions where they would be used. Consequently, transportation is already a major arctic issue, and as other arctic resources are exploited, it is likely to increase in importance.

Petroleum: The Start

Virtually every proposal for transporting oil out of the Arctic has run into opposition on environmental grounds. In addition, most conventional means of transport are either infeasible or require extensive modification because of harsh climatic conditions in these northern regions.

Surface shipping in the Arctic is subject to interruption by unexpected ice conditions, and is not generally viable on a year-round basis. The Soviet Union has invested considerable energy in developing a year-round transportation system along its northern shore, without complete success *(see page 47).* *Icebreaking oil tankers, which would be essential for regular service to North America's northern shore, are of untried design, and ice breaking consumes large quantities of fuel, raising operating costs. In addition, native peoples oppose surface shipping through the Arctic. They fear that icebreaking tankers might affect their subsistence livelihood by scaring off marine mammals; preventing effective native travel over the sea ice in winter, thus reducing their access to subsistence food resources; or harming the marine environment in the event of an accidental spill.*

Given the enormous financial investment involved in developing an arctic oil field, a reliable delivery system is crucial, and the combination of technical and economic uncertainty with political opposition from Alaskan natives has thus far deterred use of ice-breaking tankers. Instead, the Trans-Alaska Pipeline System (TAPS) has been the focus of oil transport efforts; it has operated effectively for 8 years. (For more information on these issues, see "The transportation of arctic energy resources" by William E. Westermeyer. 1984. In United States Arctic Interests. *New York: Springer-Verlag.)*

Future Oil and Gas Transport

Two trends in the exploitation of arctic hydrocarbons may affect future transport decisions: the spread of oil production to new regions and the potential exploitation of arctic natural gas reserves. As new oil producing areas are brought on line, either the TAPS network must be extended or other means of transporting the oil must be found. Extending the pipeline system is highly capital intensive, requiring assurance of a large quantity of recoverable oil before it becomes worthwhile. In contrast, a system of icebreaking tankers could be incrementally increased as new oil fields are developed. Consequently, interest in tanker transport has increased.

With respect to natural gas, the issues are even more confusing. Officially, the United States supports the development of a privately financed pipeline from Prudhoe Bay, through Canada, to the United States. But one recent estimate placed construction costs for the pipeline at $43 billion, and private industry has thus far not been able to come up with the funding. An alternative is a pipeline across Alaska to the Kenai Peninsula, where the gas would be converted to liquid natural gas (LNG) and shipped by conventional LNG tankers. Other proposals have called for converting the natural gas to LNG on the North Slope and shipping it via icebreaking LNG tankers.

Still more unusual are proposals to convert the natural gas to either LNG or methanol and ship it to Europe under the arctic ice cap via enormous nuclear or conventionally powered submarine tankers. Such tankers would be immune to ice hazards and capable of year-round operation in all weather conditions. In addition, they would cause few disruptions to arctic ecosystems, as they would travel through the productive coastal zone for only a limited period of time before moving under the permanent ice cap. They also would not disrupt the surface ice. At present such ships do not exist, and their development would have to include the training of crews and the development of underwater port facilities. There are interesting policy issues connected with the potential use of submarine tankers, as well; effective steps would have to be taken to assure that U.S. and Soviet military submarines did not interfere with the tanker traffic and vice versa.

Two types of vehicles have tremendous promise to meet arctic transportation needs: the archimedean screw tractor (AST) and air cushion vehicles (ACV). The AST is an amphibious vehicle capable of breaking its way through thin ice, and pulling itself up onto thicker ice when encountered. It is under development. Hovercraft, as ACVs are commonly known, are in use in many parts of the world; because they can operate over land, open water, ice, or any mixture of the three, they are ideally suited to the changing conditions of the Arctic. The Soviet Union has 40 ACVs in operation, ferrying cargo between shore and ships along the arctic sea route.

—FLL

MIZEX East: Past Operations and Future Plans

by Dean A. Horn

and G. Leonard Johnson

The marginal ice zones (MIZ) of the Arctic and Antarctic vary annually over an area of about 25 million square kilometers, or 7 percent of the world's ocean area. Each year, the edge of the arctic ice field migrates north and south up to 375 nautical miles. The processes and enormous energy interchange that control the location and behavior of the MIZ are of fundamental importance to meteorologists, biologists, and oceanographers. Understanding the processes that determine the MIZ is also important to ocean transport, naval operations, and environmental and living resource management. For example, sea-ice movement is a major factor in almost all aspects of arctic offshore minerals development. The dynamic nature of pack-ice must be taken into account in the location of oil exploration rigs and production platforms, logistics, transportation and construction methods.

Scientifically, the marginal ice zone was basically unknown except for limited data bases which were usually concentrated in one discipline. The Office of Naval Research (ONR), realizing the importance of the area, took the initiative several years ago in organizing a concerted international environmental science program to address MIZ processes. After a number of scientific meetings and workshops to determine the primary scientific questions and how they should best be addressed, the overall scientific issue was defined as follows: the air/sea/ice processes in the marginal ice zone form a coupled system. However, there is no satisfactory understanding of the individual processes themselves or how they interrelate.

The scientific meetings and workshops also evolved an *ad hoc* international organization of arctic scientists, the Marginal Ice Zone Experiment (MIZEX)

Science Group. This group became the corporate body for planning, coordinating, and managing MIZEX East. A MIZEX Science Plan was prepared by the Group, reviewed by the appropriate science oversight authority of each participating nation (for example, the National Academy of Sciences in the United States), and published to guide the efforts of MIZEX participants.

Subsequently, three large-scale field investigations were launched. The Bering Sea effort

The cyclonic eddy above was photographed on 5 July 1984. The center of the eddy was located at approximately 78 degrees 40 minutes North, 02 degrees 00 minutes West. Remote sensing instruments as well as in situ observations indicated this eddy had a lifetime of approximately 30 days. The diameter of the eddy is 30 to 40 kilometers. Buoys deployed within the eddy indicated a counter-clockwise orbital velocity of 0.5 meters per second. (Photo by R. A. Shuchman at 23,000 feet, courtesy of the Office of Naval Research)

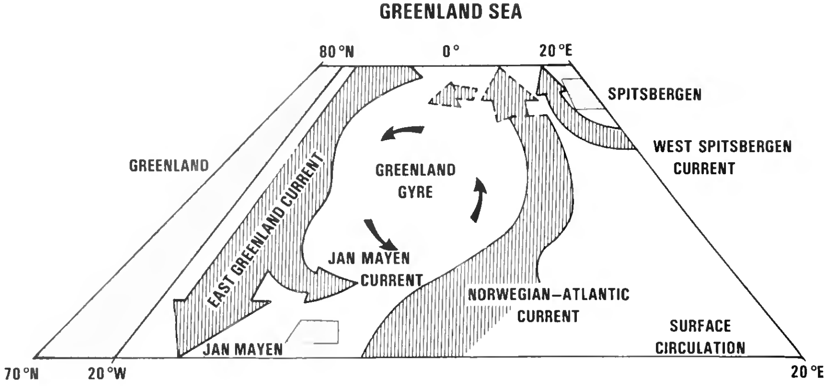

Figure 1. MIZEX East research area.

(MIZEX West) was conducted from 5 to 27 February 1983 and two MIZEX East field programs (9 June to 8 August 1983 and 18 May to 30 July 1984) were carried out in the northern Greenland Sea. This article focuses primarily on MIZEX East '84 and the planned Winter MIZEX East operations in March and April of 1987 and 1989.

MIZEX East 1984

The 1984 Marginal Ice Zone Experiment was conducted in the Fram Strait area between Greenland and Spitsbergen in midsummer during the period of greatest ice retreat (Figure 1). The culmination of more than 4 years of planning and a continuation of summer MIZEX '83, this 1984 international arctic research program utilized the resources and expertise of 11 nations and was supported by several U.S. agencies. MIZEX '84 was the largest coordinated arctic experiment yet conducted in the marginal ice zone and had the unique feature of an ad hoc organization established by the scientists themselves without any intergovernmental agreements, memoranda, or treaties.

The MIZEX '84 experiment utilized 7 ships, 8 remote sensing/meteorological aircraft and 4 helicopters, supporting a multidisciplinary team of 208 scientists and technicians, plus ship and aircraft crews. Scientists, equipment, and support came from Canada, Denmark, West Germany, Finland, France, Ireland, Norway, Sweden, Switzerland, Britain and the United States. Figure 2 summarizes this participation. Figure 3 presents an overview summarizing the MIZEX '84 experiment. Initial results from MIZEX '84 have been published as Volume 5 of the MIZEX Bulletin and are available from U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH 03755-1290, as CRREL Special Report 84-29.

Oceanographic Highlights

The region of Fram Strait is environmentally active because the relatively warm Atlantic water enters the Arctic to the west of Svalbard and cold, ice-choked arctic water exits the strait to the east of Greenland, resulting in a pronounced frontal and current system called the East Greenland Polar Front. The tremendous interchange of energy between these cold and warm waters makes the area an extremely important one meteorologically, and is thought to contribute to the formation of ocean eddies in the region. The associated shear and frontal structures make this an extremely active area characterized by complex oceanographic and atmospheric structures. Some features of Atlantic currents in the Fram Strait, below the ice, during this summer '84 season were defined. Specifically, four features appeared related to the branching of the northward Atlantic current toward the southward East Greenland current. These were:

1) the northward Atlantic current flowing along the continental slope west of Yermak plateau and entering the Arctic Basin,

2) the strong topographic features above Yermak plateau,

3) the recirculation of Atlantic waters west of the Yermak plateau along the continental slope and in the deepest part of the Straits, and

4) the southward flowing Atlantic current trapped in the East Greenland current.

Hundreds of conductivity, temperature, depth (CTD) stations were obtained by the various ships, with the shallower ones concentrated on large (mesoscale) eddies. These eddies, in turn, may contribute to the formation of atmospheric high and low pressure cells, and so may affect global weather patterns. The eddies also bring nutrients into the surface waters and so help make the ice edge one of the most productive ocean areas.

The CTD stations were used to study the size, movement, current speed, and energy content of such eddies. Tracking of 20 to 50 kilometer scale eddies along the ice edge south of 79 degrees North was carried out in coordination with the R/V *Kvitbjorn*. Location of eddies by aircraft and satellite remote sensing in near real time enabled guidance of the ship toward the eddy features. One fairly typical eddy was detected with a center at approximately 79 degrees 50 minutes North and 6 degrees 30 minutes East. The diameter of the eddy was about 20 to 25 kilometers. It was first tracked for 4 days with CTD sections taken in a "star" pattern through the eddy center and revealed almost no propagation. At the same time, the ice edge, initially located just north of the eddy center, moved northward about 60 kilometers. A second tracking period 7 days later turned up no sign of the eddy, suggesting a decay time of about 10 days. Second, a "stationary" deep

SHIPS:

USNS LYNCH	(NRL)	MAY 18 – JUNE 28
HU SVERDRUP	(NORE)	JUNE 1 – JUNE 25
MV POLARQUEEN*	(PSC)	MAY 29 – JULY 29
MV KVITBJORN	(PSC)	MAY 30 – JULY 30
MS HAKON MOSBY	(U. BERGEN)	JUNE 12 – JULY 15
FS POLARSTERN*	(A.W.I.)	JUNE 11 – JULY 18
FS VALDIVIA	(U. HAMB.)	JUNE 20 – July 18

*2 HELICOPTERS ON EACH SHIP

AIRCRAFT:

CCRS CV 580	(CANADA)	JUNE 26 – JULY 8	(8 FLTS)
CNES B–17	(FRANCE)	JUNE 30 – JULY 16	(6 FLTS)
NASA CV 990	(USA)	JUNE 8 – JUNE 30	(7 FLTS)
NOAA P–3	(USA)	JUNE 20 – JULY 7	(6 FLTS)
NRL P–3	(USA)	JUNE 24 – JULY 8	(7 FLTS)
GREENLAND ICE PATROL	(DENMARK)	MAY 29 –	(1 FLT)
RNAF P–3	(NORWAY)	JUNE 11 – JULY 18	(6 FLTS)
DFVLR FALCON	(GERMANY)	JUNE 22 – JULY 14	(20 FLTS)

MIZEX PERSONNEL (FROM 10 NATIONS):

SHIPS	164
AIRCRAFT	36
SHORE SUPPORT	18
TOTAL	208

Figure 2. MIZEX '84 field operations—May 18 to July 30.

eddy with a scale of 60 to 100 kilometers was documented by three CTD sections near the bottom.

The MIZEX '84 turbulence experiment was designed to measure mean and fluctuating currents, temperature, and conductivity at several levels in the upper ocean boundary layer beneath drifting ice. Special instrument clusters were built. These were used in conjunction with conductivity meters and oceanographic thermometers. Data from each cluster were transmitted to the surface, converted to digital frequencies by a deck unit, and recorded on floppy disk. The system is capable of handling 7 clusters (35 data channels) at a sampling rate of 6 per second.

A prototype Diode Laser-Doppler Velocimeter (DLDV) also was tested. This instrument sampled two components of flow by measuring the Doppler shift of coherent light scattered from microscopic particles in a small (1-centimeter dimension) volume. The DLDV was mounted near one of the turbulence clusters for comparison. Initial indications are that there is excellent agreement between the two instruments.

Coastal Oceanic Dynamics Application Radar (CODAR), which measures the radial component of surface currents up to a distance of 50 kilometers with a resolution of 1.2 kilometers, was successfully used by *Valdivia*. Measurements of surface currents were carried out on three sections between Svalbard and the ice edge. At the ice edge approximately 20 CODAR stations were performed.

Sea Ice

In sea ice produced in the laboratory, the relative composition of salts in the brine entrained in the ice changes as a result of the selective precipitation of the salts from the brine when the ice is cooled. Calcium carbonate is the first to precipitate, beginning to do so just below the freezing point near −2 degrees Celsius, followed by sodium sulphate near −10 degrees Celsius. Almost no studies have been done to verify the laboratory results and their geophysical implications using sea ice produced under natural conditions. Several cores of first-year and multi-year ice were collected throughout the MIZEX area. Not one showed anything like the degree of relative calcium enrichment expected on the basis of the laboratory results. Sulphate concentrations have not yet been determined, but based on the calcium data, little sulphate enrichment is expected. Fram Strait sea ice has a much lower percent of frazil versus columnar ice than does the Antarctic sea ice (26 versus 60 percent). These results seem to show that the studies of ice produced under laboratory conditions cannot be used in any simple way to describe the composition of natural sea ice.

Remote Sensing

Extensive ground truth to determine surface characterization was made in conjunction with aircraft overflights. For example, along each of the radiometer traverses, detailed studies were made of surface topography, spatial variations in snow depth, the occurrence of ice layers and lenses in the snow pack, and ponding of meltwater. These were compared with the corresponding radiometric records. At selected locations, surface characteristics were determined from core samples. For cold ice cases, these measurements included temperature, salinity, and density profiles in the snow and the top 30 centimeters of the ice together with the geometry and mean size of the snow grains. When the ice

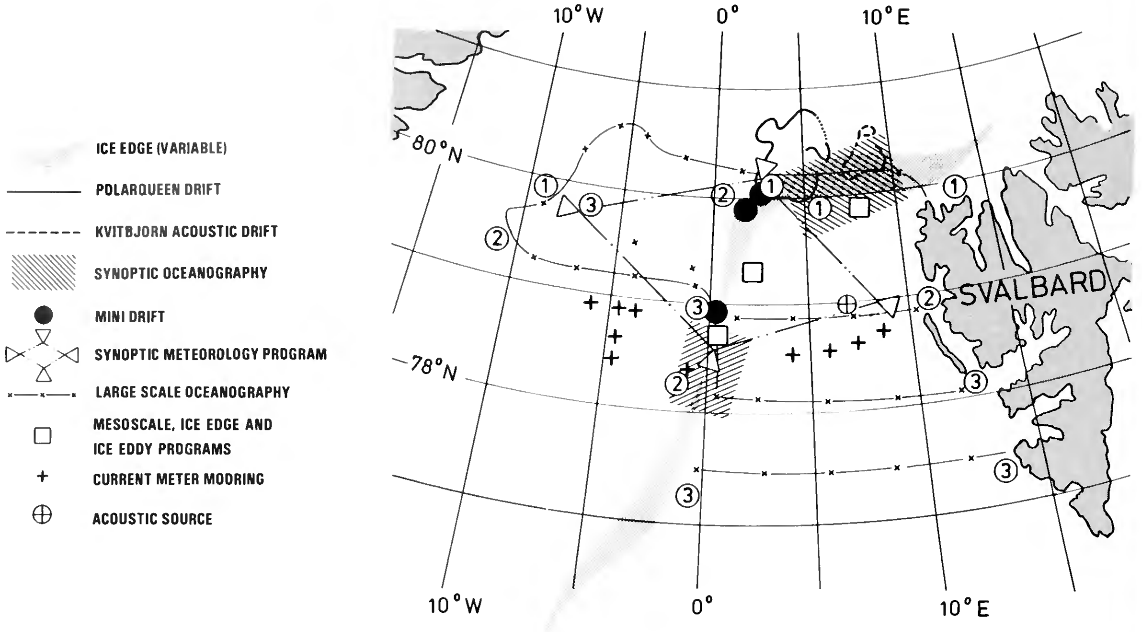

Figure 3. MIZEX '84 program overview.

entered the transition to melting stage, free water content measurements in the snow and loose upper layers of the ice were included in the program. The crystal geometry and density of the loose granular layers were also obtained.

Active and passive microwave observations were able to distinguish ice types when the surface was dry, but when the snow was wet, no clear discrimination between multi-year and first-year was possible. The synthetic aperture radar instrument (SAR) demonstrated a potential for estimating total ice concentration, but more work is needed on the algorithm. If remote sensing techniques can be improved sufficiently to be practical, they could greatly improve our observation abilities.

Meteorology

There was an extensive meteorological program connected with MIZEX '84 (Figure 3). A dedicated meteorological research plane—equipped with highly sensitive instruments to measure pressure, air-flow angle, temperature, and humidity—provided a high-resolution representation of the turbulent state of the atmosphere. In addition, upward and downward radiative fluxes were measured. A downward-looking radiometer and a radio-altimeter monitored the thermal properties and the roughness of the partly ice-covered ocean surface. The instrumentation was further extended by the use of cloud physics probes and of an aerosol/cloud water sampling device developed by the University of Stockholm. Additional meteorological data were acquired from surface vessels. The following were observed to determine, among other things, the basic processes that lead to the formation and dissipation of arctic stratus clouds: 1) turbulent fluxes of momentum, sensible and latent heat as a function of height as well as their mean values, 2) microphysical cloud properties, such as drop size distribution and liquid water content, 3) radiative cloud properties (reflectivity, transmissivity, and absorptivity), and 4) physico-chemical and optical properties of atmospheric aerosol.

Acoustics

The acoustics program for MIZEX '84 consisted of multiple sound sources and both horizontal and vertical hydrophone arrays to determine the effect of the marginal ice zone on signal propagation, coherence, reverberation, and ambient noise. An autonomous, moored, acoustic source was installed to assess the stability of surface reflected acoustic paths for tomographic application (see *Oceanus*, Vol. 25, No. 2). The source transmitted a signal similar to the type used during several earlier tomography experiments. Minor adjustments were made in signalling parameters to account for Doppler shifts caused by the ocean surface. The signal was received by hydrophones suspended through the ice.

It was determined that ambient noise levels in the 6,000 hertz range can be attributed to thermal stress when ice drifts into warmer water; the lower frequency 5 to 100 hertz noise is primarily the result of ice "quakes" as the ice breaks in response to wind and current stress.

Winter MIZEX

The planned Winter MIZEX East in 1987 and 1989 is a natural sequence to the earlier MIZ measurement

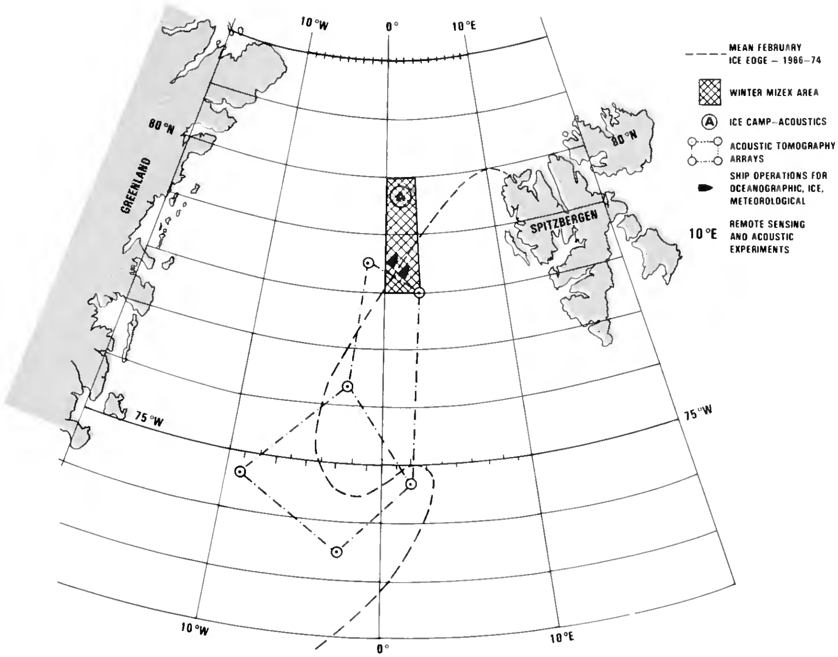

Figure 4. Winter MIZEX program scheduled for March and April 1989.

programs. The winter season emphasizes or dramatically changes certain processes; to project the flavor of scientific challenges during winter, some of the major objectives are summarized briefly here. It is planned to measure and understand:

- *Formation of arctic atmospheric lows as influenced by the large temperature and water vapor contrast at the ice edge.*
- *Growth, propagation, and decay of ocean eddies as affected by ice-edge dynamical processes, including strong winds.*
- *Shape, size, configuration, and motion of the ice field created by strong forcing of intense incoming surface waves.*
- *Snow dryness and thickness characteristic of the winter MIZ as it affects electromagnetic reflectivity and emissivity.*
- *Changes in acoustic refraction and coherence via winter-related changes in sound speed profiles, internal waves, and ocean eddies.*
- *Intensification of ice-cracking noise mechanisms as related to ocean eddies, gravity waves, and presence of recently frozen thin ice.*

While the foregoing list is not complete, efforts during MIZEX '87 and '89 will be centered on those attributes of the MIZ connected with the winter season. Beyond the focus on winter processes, special emphasis will be placed on ocean eddy phenomena. Thus eddy genesis associated with atmospheric lows and winds is a central research element. Electromagnetic sensing via aircraft and satellites will be in "real time" for identifying eddy fields. Also central to the program are acoustic interactions with eddies. Inverse methods in which acoustics become the probe for quantifying the oceanography also will be exercised and studied.

There will be five principal scientific interest areas studied in the winter MIZ environment. They are acoustics, oceanography, meteorology, ice and wave studies, and remote sensing. All data will be utilized for model studies. The especially strong role that acoustics will play in MIZEX '87 and '89 is because we are at the point of answering fundamental questions about ice noise generation and about the feasibility of MIZ ocean acoustic tomography.

Overall Experiment Strategy

The field experiments associated with the winter marginal ice program will involve three phases. The first phase, pre-1987, will consist primarily of overflights in the Fram Strait and Greenland Sea for observations of weather, sea, and ice conditions, and ambient noise monitoring. Because there is very limited knowledge of the winter MIZ environment, these flights will provide invaluable data for planning the later phases of the experiment, with particular regard to spatial and temporal scales to be expected in contrast to the summer season.

The second phase will center on a field experiment in the Fram Strait marginal ice zone in March and April of 1987. This experiment will include an icebreaker with a helicopter and fixed wing aircraft for meteorology and remote sensing. Satellite remote sensing capabilities will also be employed. Primarily, remote sensing capabilities will be used for detection and tracking of ice/ocean eddies in the winter. The program will also provide the first comprehensive data set on the oceanography of the winter MIZ, which is vital for acoustic modeling; provide the first data on important meteorological questions, including cyclogenesis and surface atmospheric boundary conditions in the winter MIZ; provide data on ice and surface gravity wave interaction; and provide ambient noise data.

The third phase will culminate in a field experiment in the Fram Strait marginal ice zone in March and April 1989. This experiment, much broader in scope than the 1987 experiment, will include an ice camp located approximately 100 kilometers to 150 kilometers from the ice edge. The location of the ice camp relative to the ice edge will be determined based upon the ice/wave interaction studies of the 1987 experiment over the course of the ice camp's 45-day lifetime. Acoustic receiving arrays and acoustic data acquisition systems as well as a meteorological station will be located at the ice camp. The tentative camp location will be west of the Yermak plateau to provide deep water—in excess of 1,000 meters—to minimize effects of bottom interaction for acoustic propagation and tomography. Figure 4 presents an overview of the proposed winter MIZEX '89 experiment.

A central idea behind the 1989 ice camp deployment is the distinct probability that much of the acoustics and ice dynamics at the camp—including ambient noise, acoustic scattering from the ice, and spatial and temporal coherence of acoustic signals (from shots deployed north of the camp)—will exhibit characteristics initially associated with deep Arctic conditions changing to conditions common to the marginal ice zone as the camp drifts from its initial location deep in the pack ice through the marginal ice zone to the ice edge.

Two helicopters will operate from the ice camp for remote acoustic and oceanographic data collection. An ice-strengthened ship with helicopters and two open ocean ships are planned for this experiment. The ice ship and one open ocean ship will be primarily dedicated to oceanography, meteorology, and ice/wave programs, while the other ship will tow an array and/or acoustic source(s). Fixed bottom moored acoustic sources and receivers will be deployed in the Greenland Sea and in the Fram Strait area. These sources and receivers will be part of both the Greenland Sea Project's long-term ocean acoustic tomography program as well as the MIZ '87/'89 program. These sources and receivers will be deployed in the spring of 1988 and recovered in the spring after MIZEX 1989.

With the experience gained from 1987, a major emphasis of the 1989 experiment will be to identify ice-ocean eddies, other large-scale oceanographic phenomena, and internal waves in real time using remote sensing. Then scientists will conduct intensive oceanographic measurements and simultaneously position the ship-deployed acoustic sources and ship/helicopter-deployed acoustic receivers to obtain the desired propagation and ambient noise geometry with respect to the eddy and ice fields.

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The F.S. Polarstern at an ice and oceanographic station during MIZEX '84 program. (Photo courtesy of the Office of Naval Research)

Data Management

All MIZEX data—so as to be readily available and most useful to the scientific community—are being placed in the National Snow and Ice Data Center (NSIDC) in Boulder, CO (303-492-5171) so that they can be readily available to the scientific community.

The majority of MIZEX West and MIZEX '83 data are in the form of reports and tapes readily accessible. MIZEX '84 data and reports are being added to the data bank as soon as they are received by NSIDC. An index (inventory) of the MIZEX holdings at NSIDC is available, on-line, on Telemail's MIZEX Bulletin Board.

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An artificial ice island with drilling rig offshore in the Beaufort Sea. (Photo courtesy American Petroleum Institute)

Arctic Offshore Petroleum Technologies

by James W. Curlin, Peter Johnson, William Westermeyer, and Candice Stevens*

Only one technological challenge is more difficult than drilling for oil in the Arctic—drilling for oil beneath the ocean in the Arctic. The expense of exploring and developing arctic petroleum offshore is much greater than the cost of producing oil in the shallow waters of the Gulf of Mexico, off southern California, or even in the onshore Arctic.

Skeptics persistently doubt the ability of the offshore industry to safely explore for and develop oil and gas fields under harsh ocean conditions. However, it should be remembered that some said it could not be done in the North Sea, with its howling winds and high seas. Others swore that routine drilling in water over a mile deep using risers and dynamically positioned drill ships would not work.

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* Other members of the Office of Technology Assessment Project team include Daniel Kevin, Cheryl Dybas, and Nan Harllee.

Many still maintain that arctic conditions—sea ice, permafrost, changeable weather conditions, remoteness, long periods of winter darkness, and exposure to bitter cold—are too risky. To set the record clear, Congress directed the Congressional Office of Technology Assessment (OTA) to assess the status of offshore oil and gas technologies for arctic and deepwater operations.*

The OTA found that the offshore industry is technologically prepared to explore the frontier regions at a pace consistent with national goals and industry objectives. Conclusions about production systems were less certain, because few frontier wildcat wells have proven to be commercially developable. However, industry experience suggests that no significant barriers prevent modifying production systems for deployment in the Arctic.

The OTA's report cautioned Congress about oil spill cleanup in broken ice and rough waters. However, possible shortcomings in cleanup strategies and technologies are offset by the industry's outstanding spill-avoidance record and the excellent technologies available to monitor and shut down wells in the event of an emergency.

Offshore Drilling Technology

Drilling technology has come a long way from the cable tool used to drill Colonel Edwin Drake's Pennsylvania well in 1859, an event which ushered in the oil era. A new technology—the rotary drill—used in the Spindletop well in Beaumont, Texas, in 1901, led to events that changed the future and set the stage for petroleum-based transportation systems. The rotary drill was first used to bore under water in Caddo Lake, Louisiana, in 1911; the first truly offshore well was drilled by Mobil in the Gulf of Mexico in 1945; and the first well drilled out of sight of land was in 1947. Since then, offshore oil and gas technologies gradually have been modified for use in ever deeper waters and harsher environments.

But during the 40 years of offshore drilling, changes in the industry have *not* been as revolutionary as some believe. Advances have generally resulted from extending and adapting proven technologies rather than developing radically new engineering concepts. Despite its reputation for bravado and daring, the offshore oil industry is extremely conservative and cautious about innovation and technology. Advances in computers, microprocessors, downhole sensors, navigation systems, ship-positioning systems, advanced materials, and diving technology now allow the industry to drill and produce oil from below the ocean more precisely and safely. But the Oil Patch** has proceeded slowly and cautiously in moving this space-aged technology offshore.

Oil Exploration in the Arctic

The industry felt its way seaward with similar caution in the Arctic. Alaskan operators have had the advantage of Canadian Arctic experience gained from exploring the Canadian Beaufort Sea beginning in 1960. Exploration there has accelerated since 1980 under Canada's National Energy Plan, which aims at rapid exploration of offshore areas.

In the southern region of the Bering Sea, wind, waves, currents, unstable seafloors and seismic activity are more hazardous than ice. Conditions are more like the storm-prone North Sea than the Arctic, and engineers have relied on European experience for design and operation.

Oil activity in the Alaskan Arctic began in 1968 when the discovery of the giant 12 billion barrel onshore Prudhoe Bay oil field led to the construction of the Trans-Alaskan Pipeline System (TAPS) in 1977. Petroleum companies then ventured into the Beaufort and Bering Seas, and are now poised for a try in the even more hostile Chukchi Sea.

The offshore industry used conventional land rigs positioned on natural islands when it drilled the first well from a pier in Santa Barbara, California, in 1897; ever since then, the industry has used similar, arctic-adapted rigs in arctic waters, starting with the first wells in 1974. Later, in 1977, similar land rigs were placed on artificial islands—gravel or ice—constructed near shore in shallow water (less than 60 feet). For deeper, ice-prone waters, refloatable concrete gravity structures—concrete island drilling structures (CIDS)—are now being used in the Alaskan & Canadian Beaufort Sea. In the Bering Sea, where exploration began in 1982, sea ice is much less a problem, and the summer drilling season's ice-free conditions allow the use of conventional semisubmersibles or jackup rigs, similar to those developed for temperate regions.

Costs

Even if arctic offshore technology does not look much different than its warm-water cousins, the price tag for a chance at the brass ring is a lot higher; economics rather than technology limits arctic petroleum development. Exploration and production at the arctic frontier may cost 10 to 100 times more than comparable operations in the mature Gulf of Mexico. The average cost of drilling exploratory and appraisal wells in the near-shore Gulf of Mexico is about $5 or $6 million per well. The average cost for arctic exploratory wells is estimated to be $50 to $60 million each, although costs vary significantly within the region. Sohio's single Mukluk exploration well in the Beaufort Sea reportedly cost $140 million by the time it was abandoned in 1984. A total exploration program in the Gulf of Mexico may cost $80 million, while a comparable program in the Navarin Basin will likely cost more than $800 million.

Field development costs also run much higher in the Arctic. A 50 million barrel field in the Gulf of Mexico costs $100 to $200 million to develop. The development of a commercial arctic field—which must contain one or two billion barrels of oil to pay

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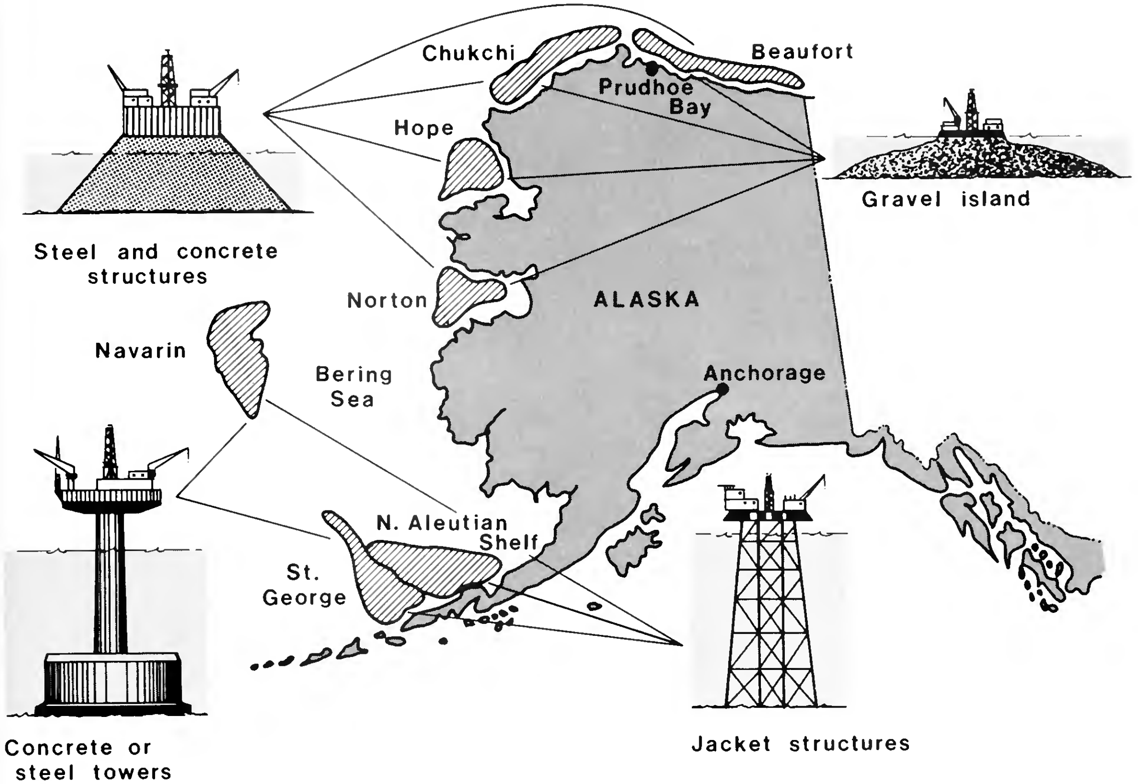
* *Oil and Gas Technologies for the Arctic and Deepwater*, (Washington, DC: U.S. Congress, Office of Technology Assessment, OTA-0-270, May 1985), 219 pp.

** The collective group of petroleum industries are often referred to as the Oil Patch.



Different types of arctic oil production structures used for offshore development.

its way—may range from $6 billion in the Beaufort Sea to more than $10 billion in the Navarin Basin.

Other expenses, such as operating and transportation costs are also much higher in the Arctic because it is remote and lacks transportation systems. After taxes, and allowing for a 10 percent profit, the estimated breakeven price per barrel of oil from the near-shore Gulf of Mexico ranges from $17 to $27, compared to an estimated minimum of $28 to $32 for the Arctic (averaging over $30 for most arctic areas). If profit is the goal, today's* $18.00 to $20.00 world price for oil will not allow much profit from new arctic oil.

To make the picture even gloomier, arctic natural gas is not likely to be economically competitive for a long time. In the parlance of drawpoker players, the industry is "betting on the come" when prices stiffen and the current oil glut is gone in the 1990s.

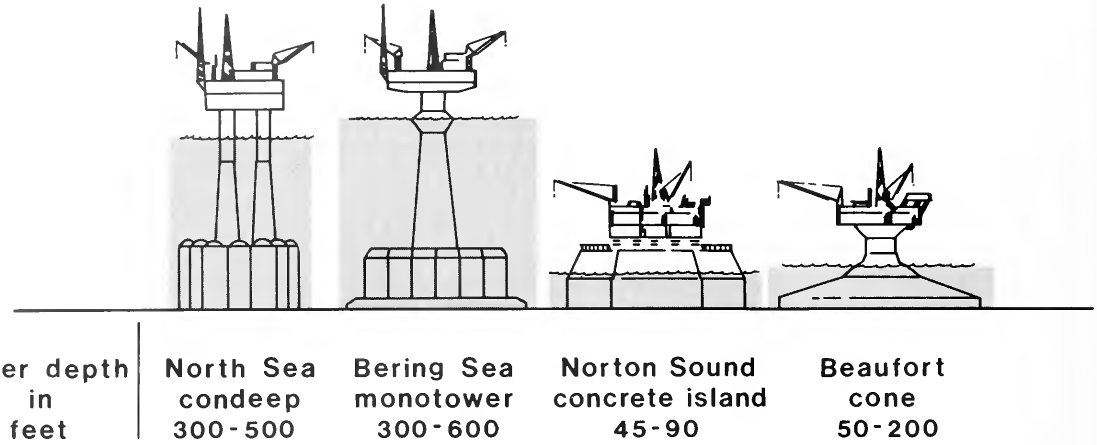
Because of higher costs, longer lead-times to production, and lower profit margins in the Arctic, only very large fields can offset costs and still yield an adequate return. Whereas a 500 million barrel field may be considered a giant in the 48 contiguous states, it could go unproduced in parts of the Arctic because revenues would not cover development costs. Companies must, therefore, set their sights for arctic "elephants"—those fields containing billions of barrels of oil. Unfortunately, exploration history has shown that few of those are likely to exist.

* As of late January, 1986.

Too Few Elephant Fields

So far, the results of Alaskan arctic offshore exploration have been disappointing. Only two commercial discoveries have been made—Sohio-Exxon's 350 million barrel Endicott field, and Shell's 300 million barrel Seal Island discovery—both in nearshore areas adjacent to Prudhoe Bay. If both fields were not close to the onshore transportation and service facilities of the North Slope, they probably would be considered submarginal economically. Elsewhere, in the Norton and Navarin Basins, the few exploratory wells drilled thus far have been non-producers. As yet, there are no producing wells in the U.S. arctic outer continental shelf (OCS).

Once considered to be the most promising future source of petroleum among U.S. offshore provinces, expectations for the Alaskan Arctic have recently been lowered by the Department of the Interior. In 1981, the U.S. Geological Survey estimated that the Alaskan OCS might contain 45 percent of the nation's offshore oil or about 12.2 billion barrels of economically recoverable oil. Given the unsuccessful exploration record so far, it is now expected to account for 27 percent of total offshore



Different types of oil rig structures are used depending on the depth of the water.

resources, or about 3.3 billion barrels—a reduction of 73 percent from the 1981 estimate.

The offshore industry once thought that the Beaufort Sea held the best prospects for large discoveries, but when Mukluk and nearby Antares wells failed to find oil on what was expected to be the largest and most productive geological structure in the area, resource estimates have been downgraded from 7.8 billion barrels in 1981 to less than a billion barrels in 1985. The Navarin Basin, where exploration has just begun, is now considered the best prospect with an estimated 1.3 billion barrels of economically recoverable oil. Estimates of economically recoverable petroleum are subject to extremely large errors and uncertainties—at best they are "guesstimates"—so until there is considerably more exploration in the Alaskan Arctic, we will not know its true potential.

There's A Will: Is There A Way?

The future for Alaskan arctic offshore oil and gas is unclear. Even though exploration results thus far have been disappointing, the Alaskan Arctic still holds more promise for large discoveries than other frontier OCS regions—such as the Atlantic, northern Pacific, and Gulf of Alaska. With characteristic optimism, the offshore industry continues to be enthusiastic about the Arctic.

But current economic turmoil in the petroleum industry—mergers, takeovers, and buyouts—is leading to major restructuring in the heretofore stable industry. Simultaneously, world oil prices have tumbled to their lowest level since 1973, and they may slide even lower before 1990. These forces have combined to affect the debt and earning ratios of even the largest companies. Some of the most aggressive companies are reducing their exploration budgets in response to the economic pinch. How this will affect the pace of offshore exploration in the high-stakes Arctic is uncertain. It is important to Americans that the industry continue a healthy and robust arctic exploration program to prove or disprove the existence of major energy resources there.

In planning its energy future, the United States has tacitly assumed that immense quantities of oil and gas lie beneath the OCS. Thus far, there is little evidence that the OCS holds the potential we once thought it did. Outside of the proven producing areas of the Gulf of Mexico and southern California, no new major fields have been discovered offshore. Even if a couple of new "elephant-size" discoveries were made in the Arctic, their impact on future U.S. energy supplies, while important, would be small compared to anticipated needs. The Department of Energy projects that the U.S needs to discover and produce 2.9 billion barrels of oil each year to offset that now being consumed from proven reserves.

Currently, after 30 years of exploration and production, only 4.6 billion barrels of oil are estimated to be discovered and recoverable in all of the OCS (6.4 billion barrels have already been pumped); this is only 1.6 times more than that which must be discovered each year from here on just to keep the ledger even. Providing the pace of exploration continues in the Arctic, we should know a great deal more about the oil and gas potential of that region as highly promising areas are drilled during the next 5 years. If by the early 1990s we


The trans-Alaska pipeline in winter. (Photo courtesy American Petroleum Institute)

The largest man-made gravel island ever built in U.S. waters. Called Mukluk, it is located 65 miles northwest of Prudhoe Bay in the Beaufort Sea. (Photo courtesy American Petroleum Institute)

have not discovered something akin to the Prudhoe Bay field in the nation's last major offshore frontier—the Arctic—the United States will have to reappraise its energy policy regarding liquid fuels. At that time, the federal government may need to assume more of the financial risk of costly offshore exploration as the industry starts the second round of exploration for outer continental shelf oil and gas.

James Curlin is currently a Senior Associate at the Congressional Office of Technology Assessment (OTA). He directed the OTA study, Oil and Gas Technologies for the Arctic and Deepwater. Peter Johnson is a Senior Associate with the Congressional Office of Technology Assessment. William Westermeyer is a Staff Analyst with the Congressional Office of Technology Assessment and was co-editor of United States Arctic Interests: The 1980s and 1990s. Candice Stevens is currently associated with the Organization for Economic Cooperation and Development (OECD) in Paris, France. She previously was Senior Analyst with the Congressional Office of Technology Assessment.

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Soviets Shelve Plan on Diverting Rivers in Arctic Regions

A Soviet official announced in Moscow on March 4th of this year that the Soviet Union was postponing a plan to divert water from rivers in European Russia that flow into the Arctic Ocean.

"At present, we can manage without the switching of water from the northern rivers," Leonard Vid, Deputy Chief of the State Planning Committee (Gosplan), told a news conference. Vid's comments came in the wake of a Communist Party Congress and were reported by Reuters News Agency and *The Los Angeles Times*.

The water diversion plan had been included in the November draft of the Soviet five-year plan for 1986–90. *The Los Angeles Times* characterized Vid's statement as "at least a temporary victory for Soviet writers concerned with the environment, who have mounted an unusual campaign against the river projects in the state-run media" in recent months.

The postponement follows the shelving of a more ambitious plan to divert water from Siberia to Central Asia. This project was not included in the draft of the new five-year plan.

Critics of both projects, according to *The Los Angeles Times*, argued that diversions of water from rivers flowing into the Arctic Ocean might change weather patterns not only in the Soviet Union but around the world. In addition, the critics held that the projects would inundate some ancient Russian towns, and affect fishing, rainfall patterns, and river navigation.

The projects basically broke down into two parts: by the year 2000, it was planned that some 20 cubic kilometers of water per year would be diverted southward from the European north region; another 27 cubic kilometers of water was planned to be diverted from western Siberia into Kazakhstan and Central Asia shortly after the year 2000. However, the status and time frame for this project is presently unclear. During the first half of the next century, diversions could increase to around 60 cubic kilometers in each region, or a total of 120 kilometers a year (the annual flow of the Mississippi River as recorded at the mouth is 600 cubic kilometers).

During the last decade, concerns have been expressed by researchers in the West that Soviet river diversions, by altering the Arctic ice cover, could possibly affect the climate of the Northern Hemisphere. The argument put forward is that freshwater inflow to the Arctic Ocean has a significant influence on ice conditions and that changes in that discharge could affect the ice cover which in turn influences atmospheric pressure and circulation patterns over the entire Northern Hemisphere.

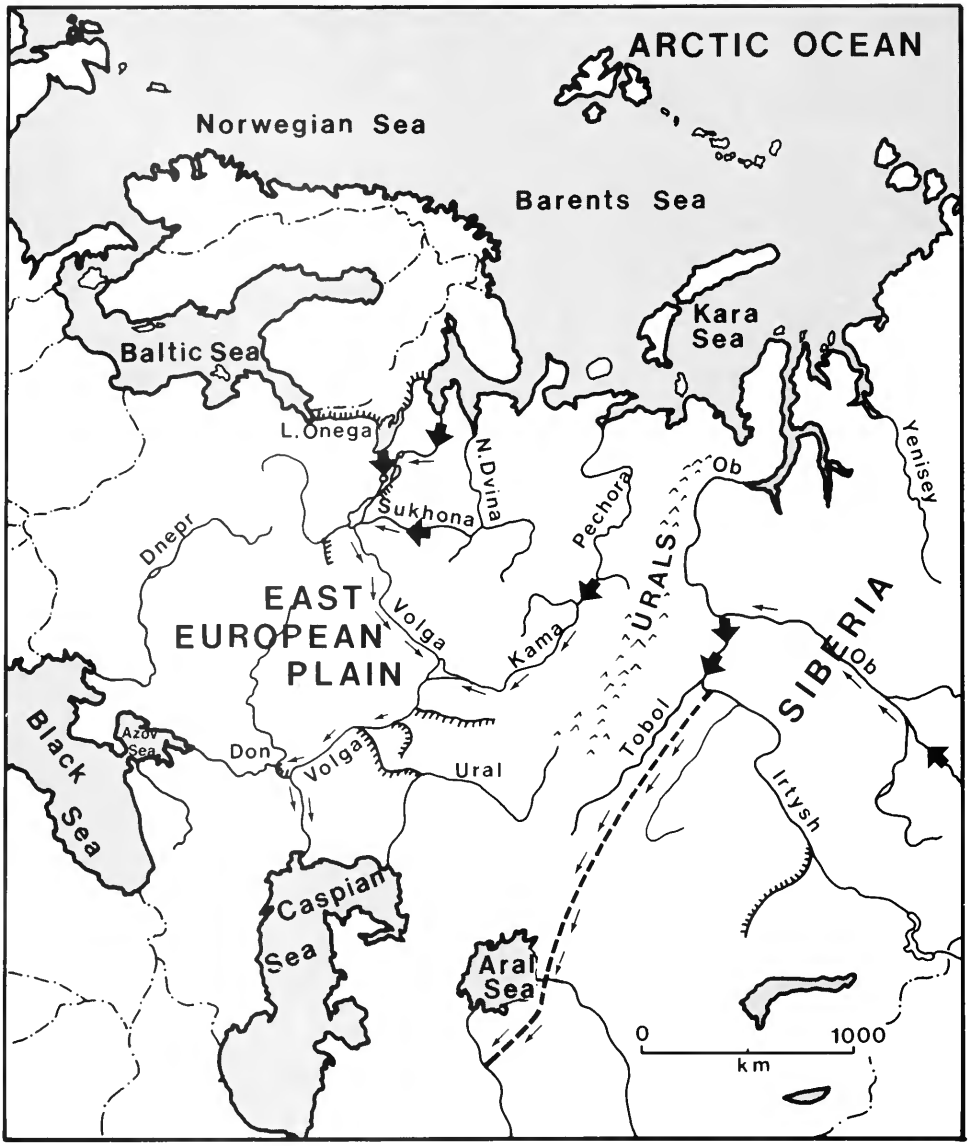
Opinion among investigators both within and outside the Soviet Union is divided as to whether diversions, assuming they have detectable effects, would increase or decrease the ice cover and lead to arctic cooling or warming.

Most researchers are confident that the relatively small European diversion projects planned to operate before the end of the century will have little effect on ocean circulation or sea ice distribution. They are less sure about the larger-scale diversions planned for the 21st century that will affect the Kara and Barents seas. They also point out that modeling studies undertaken in the late 1970s on ocean circulation and sea ice distribution in the Arctic have limitations.

The October 1984 plenary meeting of the Central Committee of the Communist Party confirmed the Soviet government's intention to proceed with the diversions of its rivers. The Council of Ministers, the highest governmental organization, and the Central Committee of the Communist Party adopted a joint resolution on land reclamation through river diversions covering the years 1986 through 2000. News of the European phase of the project has received a great deal of attention in the Soviet press and was mentioned in November of 1985 as part of the next five-year draft plan. The Siberian part of the water redistribution project also has received widespread publicity in the press up to September of 1985, when all mention of this phase of the project disappeared from the media.

Eighty-four percent of the Soviet Union's river flow enters the Arctic and Pacific oceans. The rest crosses the country's southern and western portions, most of which have arid or semiarid climates. These latter lands are inhabited by about 75 percent of the population, account for 80 percent of economic activity, and contain more than 80 percent of the nation's cropland, including all of its more fertile regions. They also have become increasingly reliant on irrigation as a means of increasing and stabilizing harvests.

The European first-phase



Region where the Soviet Union was planning to divert some rivers. Arrows indicate routes of planned flow.

construction, which reportedly was already under way with the construction of roads, concrete batching plants, and workers' quarters, was scheduled to be transporting 5.8 cubic kilometers of water a year into the Volga basin by 1995. The cost of initial first-phase facilities has been estimated at 600 million rubles in 1982 prices (roughly $800 million). Second-phase costs have been estimated at 1.8 billion rubles, bringing the total price tag in European facilities to 2.4 billion rubles (more than $3 billion).

The primary purpose of the first-phase European diversion was to enhance water supplies in the drainage basins of the Caspian and Azov Seas, where water resources are believed inadequate to simultaneously meet the needs of irrigation, hydroelectricity, transportation, and fishery requirements in the future.

The Siberian Diversions

Construction on the Siberian river diversions was planned to begin as early as 1988 if approved by the Council of Ministers this year. Water transfers were scheduled to begin during the latter half of the next decade, although all facilities would not be completed. However, there was no mention of Siberian transfer projects in the guidelines for the new five-year plans (1986–1990).

The Siberian diversions also were planned in two phases. Phase one would take 27.2 cubic kilometers annually from the Ob' and its tributary, Irtysh, and send it southward. The transfer route would stretch from the confluence of the Ob' and Irtysh rivers in the central part of the west Siberian Plain to the Syrdar'ya River in Central Asia—a distance of 2,544 kilometers.

Capital cost of the first-phase of the Siberian diversion was estimated at nearly 14 billion rubles (about $17 billion). However, this is only for construction of the route from the Ob' to the Amudar'ya. Another 18 billion rubles ($23 billion) would be necessary for irrigation and for other facilities to use the water.

Many Soviet water management specialists consider the

Table 1. Characteristics of Soviet River diversion projects.

Project	Source of diversion	Average annual diversion (km³)	Average annual flow reduction at diversion point (%)	Average annual south flow reduction (%)	Reservoir area (km²)	Status
			EUROPEAN PROJECTS			
FIRST PHASE						
First stage	a. Lakes Lacha & Vozhe	1.8	52.9[1]	11.5[1]	27	
	b. Lake Kubena & upper Sukhona River	4.0	42.6	3.6[2]	67	
	First stage total	5.8			94	
Second stage	a. Lake Onega	3.5	19.9[3]	4.5[4]	7	
	b. Upper Pechora River	9.8	51.0	7.5	2,170	
	Second stage toal	13.3			2,177	
	First phase total	19.1			2,271	
SECOND PHASE	a. Lower Sukhona & Malaya Northern Dvina rivers	10.2 (14.2)[5]	(59.2)[5]	(13.0)[5]	230	Implementation possible in first decade of next century.
	b. Lake Onega	3.6 (7.1)[5]	(9.0)[5]	(9.0)[5]	none	
	Second phase total	13.8			230	
	First and second phase total	32.9			2,501	
ONEGA BAY RESERVOIR	Rivers influent to Onega Bay	27.6	69.0	69.0	unknown	Implementation possible in first half of next century.
European diversions total		60.5			2,501	
			SIBERIAN PROJECTS			
FIRST PHASE	a. Irtysh River at Tobol'sk	17.0	25.4			
	b. Ob' River at Belogor'ye	10.2			unknown	
	First phase total	27.2	8.5	7.1		
SECOND PHASE	Mainly Ob' River at Belogor'ye (with possible compensation from Yenisey River)	32.8				Possible implementation during the first half of the next century.
Siberian diversions total		60.0	18.8[6]	15.7[6]	unknown	

NOTES: [1]Onega River; [2]Northern Dvina River; [3]Svir' River; [4]Neva River; [5]Includes earlier stages and phases of diversion; [6]Excludes effect of compensation from Yenisey River. Source: Micklin.

rapid implementation of Siberian transfers to be imperative because of what is widely viewed as a worsening water supply situation in Kazakhstan and Central Asia.

The Soviet river diversion project would have environmental, economic, and sociocultural impacts ranging from the Arctic Seas of the USSR to the country's southernmost regions. More than 120 Soviet institutions, including the Academy of Sciences, the State Committee for Hydrometeorology and Environmental Control, and various government ministries, have been involved in researching the river diversion project.

The research by Soviet scientists on the possible effects of planned diversions reportedly has been careful and detailed, making use of systems analysis and numerical models, with their associated computer algorithms. Nevertheless, one Western expert feels "these projects are of such scope and complexity and represent such a profound interference in the natural environment that no matter how carefully planned, implemented, and operated they may be, significant impacts—including those difficult to foresee—are unavoidable."

Soviet researchers for years have been aware of the potential of river diversions to alter the arctic ice balance. They have concluded that diversions of up to 60 cubic kilometers annually from the Ob' and Yenisey rivers (both flowing into the Kara Sea) would amount to a reduction of less than 2 percent of freshwater discharge to the Arctic Ocean and thus would not have any perceptible Arctic-wide effects. Independent research in the West supports these conclusions. Indeed, a sophisticated effort at modeling the changes in arctic ocean circulation and ice extent owing to diversions by Albert Semtner of the National Center for Atmospheric Research (NCAR) showed little effect even from large fresh water inflow reductions. Nevertheless, Soviet, as well as some Western researchers, continue to believe that the larger diversions being considered for these rivers in the next century could possibly trigger measurable changes.

Preliminary calculations by researchers at the Arctic and Antarctic Institute in Leningrad indicate that a 1 percent reduction of inflow to the Kara Sea could result in a 1.5 percent increase in the summer extent of ice in the sea. "Thus," according to a Western expert, "a 25 cubic kilometers diversion (2 percent of the 1,350 cubic kilometers estimated to enter the Kara Sea on an average annual basis) could result in a 3 percent greater ice cover. A 60 cubic kilometer diversion (more than a 4 percent decrease in inflow) could lead to a 6 percent growth. Larger diversions might have an even greater effect."

What is clear from talks with Western researchers who follow the Soviet project to divert its rivers is that past studies on the potential effects of these changes on climate are limited in scope and relatively primitive in concept. They state that considerably more research is needed on the subject *before* not *after* we find our climate may have been altered by large-scale water transfer projects.

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Editor, Oceanus

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Bowhead Estimates Revised Upward; Hunt Issues Ease

For the past 10 years, the hunting of the bowhead whale, *Balaena mysticetus*, by the Alaskan Eskimo for subsistence purposes, has been a subject of national and international controversy. On one side, the Eskimos are fighting for the right to continue hunting an animal deeply associated with their culture. In direct conflict with this is the belief of the Scientific Committee of the International Whaling Commission (IWC) that the size of the bowhead whale population is critically low.

The Eskimos of northern Alaska began hunting the bowhead whale more than 2,000 years ago. As do today's Eskimos, the primitive Eskimos whaled during an eight-week spring hunt when the bowhead passed by on their annual migration from the northern Bering Sea to their summer feeding grounds in the eastern Beaufort Sea.

Traditionally, bowhead whales were hunted from skiffs called umiaks, which were covered with sealskin or walrus hides. The bowheads were struck with harpoons to which a series of floats were attached. The floats were vital; they not only impeded the whale's swimming, but also indicated the direction in which the whale was moving and the points at the surface where the whale would reappear. The whale was then chased, exhausted, and killed with lances. John R. Bockstoce, curator of ethnology at the New Bedford Whaling Museum in Massachusetts, has estimated that prior to the influence of Yankee whalers, Eskimos were capable of taking 45 to 60 bowhead whales annually (from a stock size estimated at 18,000).

During this time, the Eskimos used the entire whale for food, tools, weapons, utensils or toys. Because the bowhead whale fulfilled all these needs, Eskimo culture evolved elaborate cultural and religious customs associated with it. As daylight returned in late winter, the activities surrounding the hunt began. They included cleaning and repairing the harpoons, lances, and sealskin floats, and covering the boats with new walrus skins. New clothes had to be made, since, for religious reasons, the crew could not approach the whales in clothing previously used in hunting.

In early spring, prior to the hunt, the crew would go into isolation for four days of intensive religious preparations to ensure a safe and successful expedition. Amulets or religious charms were placed in the boats to aid and protect the crew during the whale hunt. When a whale was finally killed, towed to the ice edge, and pulled ashore, an elaborate ritual in which a formal greeting was bestowed on the bowhead was performed. The whale was then cut up by the entire community and distributed among all the villagers. At the end of the spring whaling season, a religious and social festival was held that lasted for days. The same customs are followed today.

Early Commercial Whaling

For centuries the bowhead whales and the Alaskan Eskimos existed as co-inhabitants of a presumably stable ecosystem. It was not until the advent of the Yankee whaler in 1848 that this stable ecosystem was altered drastically. Yankee whalers first took the bowheads in 1843 off the Kamchatka Peninsula in the Bering Sea (Figure 1), but it was not until 1848 that a Yankee whaler, Captain Thomas Roys, discovered the Western Arctic Stock, a large population of bowhead whales in the Bering Strait.

Out of what are considered the five distinct populations of bowhead whales that had once roamed the northern waters, the Western Arctic Stock was the only one that had not been decimated by commercial whalers, and remains the largest stock today. Therefore, news of the new, rich whaling grounds spread quickly; by 1852, more than 200 whaleships operated in the general area of the Bering Strait.

From 1850 to 1854 about 1,500 whales were taken. Oil and baleen were the main products utilized from the whales. Commercially, whale oil was used for illumination; lubrication; tanning leather; and manufacturing soap, paint, and varnish. Baleen was used to make such products as watch springs, corset stays, skirt hoops, combs, and furniture. The demand for whale oil and baleen was so high that by 1880 the baleen and blubber of one large bowhead whale were worth more than $10,000.

During 1885, hoping to increase their catch, commercial whalers established shore based stations all along the northern coast of Alaska to hunt the bowhead in Eskimo fashion during the spring migration. It was during this time that many natives adopted new hunting equipment from the Yankee whaler—such as the darting gun and the shoulder gun. The darting gun was mounted on the harpoon shaft and fired a small bomb into the whale the moment it was struck; the shoulder gun fired a similar bomb from a distance and aided in killing a wounded whale. Both guns, when used correctly, were quite effective in aiding in the killing and capture of the whale. Thus, they greatly minimized the number of "struck but lost" whales.

In its first few years, shore-based whaling prospered with a four-fold increase in the number of whaling crews. Consequently, the number of whales killed increased proportionately. However, the large catches were short lived. By 1915, the commercial hunt had ended because of the decline in the bowhead whale population and the collapse of the whalebone market.

Two views of Alaskan Eskimos hauling bowhead whales out of the water. The bowhead is central to the indigenous culture. (Larger photo by C.D. Evans, Arctic Environmental Information and Data Center; inset photo by W.M. Marquette, National Marine Mammal Laboratory)

Subsistence Hunting

After commercial whaling, the Alaskan Eskimo subsequently returned to subsistence hunting. This time, however, they were harvesting a severely depleted population. This subsistence hunting has continued up to the present. Up until the 1970s, catch levels hovered at between 10 and 15 whales per year; most whales struck were also caught.

In the 1970s, the situation changed abruptly when the number of subsistence crews increased dramatically, nearly doubling in size. The increase was the result of whaling being reinstated in three communities where it had lapsed, and the fact that the number of crews participating in the hunt had grown in communities where there has been a continuous whaling history.

The dramatic expansion in the number of crews resulted in a significant increase in whale harvests. Between 1973 and 1977, respectively, a total of 47, 51, 43, 91, and 111 whales were struck or killed. Since 1973, there has been a drastic increase in the amount of struck but lost whales; whales that had been struck by darting or shoulder guns but were never captured. It is unknown how many of these whales may have been injured seriously enough to die.

Three factors that could explain the increase in whaling effort and catch between the years of 1970–1977 are economic, ecological, and cultural in nature. Growth in the number of whaling crews seems to have coincided with a period of economic expansion in the North Slope region of Alaska. The increased access to cash allowed more individuals to finance their own crew. One could also purchase modern equipment, such as outboard motors for the boats and motor sleds for onshore transportation, which made whaling much easier and therefore, more accessible. However, there have been other times when a dramatic growth in cash accessibility did not result in such an increase in the number of whaling crews. This indicates that while economic factors may play a role, other non-economic factors appear to be of equal or greater significance.

Edward Mitchell and William M. Marquette have reported that the Eskimos are convinced that bowhead whale populations have increased over the last 15 years. In the Eskimos' view, expansion of the whaling effort, along with increased catch, indicate a thriving bowhead population.

There also has been an increased interest in the revitalization of native traditions during the last 15 years. There has been a focus on the importance of subsistence activities, particularly that of the bowhead hunt, as a way of expressing commitment to a particular and meaningful cultural identity.

Ban on Hunting

Trends of high landings, losses, and improper whaling techniques alarmed the Scientific Committee of the IWC. Concerned about the recorded high landings in 1976, the IWC passed a resolution recommending, ". . . that contracting governments as early as possible take all feasible steps to limit expansion of the fishery and to reduce the loss rate of struck whales." Although others hunted the bowhead whale, such as the Inuit in Canada and Siberian natives in the Soviet Union, the resolution was primarily aimed toward the United States.

In 1977, the Scientific Committee of the IWC recommended that the IWC rescind an exemption that had, since 1931 permitted aboriginals to take bowheads, and they recommended a zero catch of the bowhead in Alaska. These proposals were based on the following premises: 1) the current population of the bowhead was estimated to be somewhere between 600 and 1,800 individuals; 2) this was less than 10 percent of the estimated initial population size; 3) the Eskimo harvest had increased appreciably in the last few years, primarily as a result of an increase in hunting efforts; and 4) the harvest risks for the species were unacceptably high. In June 1977, the IWC called for a moratorium on the hunting of all bowhead whales along with the nullification of the aboriginal exemption clause of 1931.

The decision surprised Alaskan Eskimos. Their first reactions were shock and anger. Stressing the importance of the bowhead to the Eskimo culture, many stated that they would continue to hunt, regardless of what the IWC had to say.

The IWC action placed the U.S. government in an awkward situation. Since the early 1970s, the United States had strived for whale conservation and strict limitation of commercial whaling around the world until whale stocks recovered. It also promoted a greater worldwide recognition of human, particularly minority, rights. Any actions hindering the Eskimo whale hunt put these two policies in direct conflict.

Under the Whaling Convention Act, which committed the United States to participation in the IWC, the U.S. government could within 90 days object formally to the IWC's ruling. If the U.S. government objected, they would then have the legal right not to adhere to the ban. However, this course of action would have put the U.S.'s commitment to protect the whales in question, and could have seriously affected worldwide whale conservation programs.

By October 1977, it became apparent that the United States would not file a formal objection to the IWC ruling, not wanting to jeopardize its hard-won gains in fostering international conservation measures for the whales.

In Barrow, in late August 1977, the Alaskan Eskimo whalers decided to take matters into their own hands, with the formation of the Alaskan Eskimo Whaling Commission (AEWC). The AEWC was made up of 70 whaling captains from all the whaling communities. Its first major action was to deny the IWC jurisdiction over subsistence whaling activities. Stating that a zero quota was not acceptable, they began efforts to overturn the moratorium.

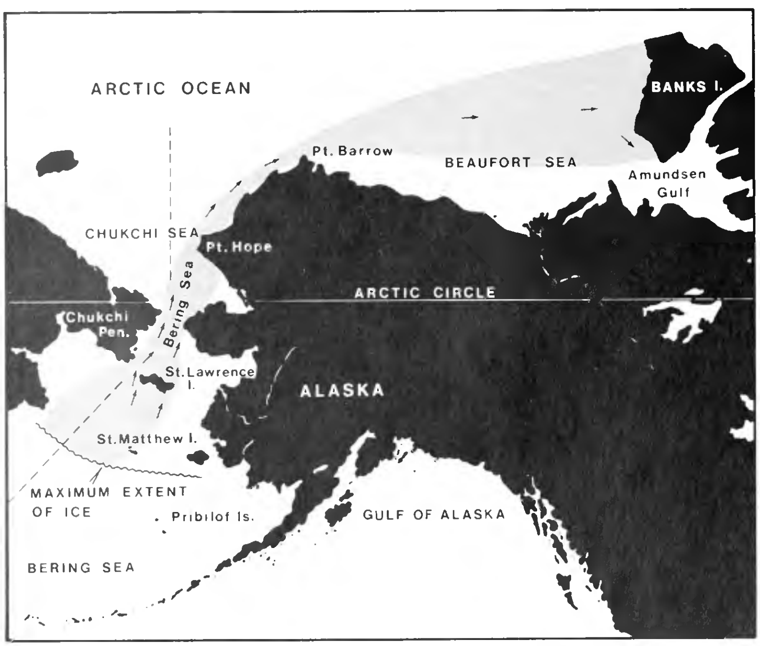
The AEWC's struggle to overturn the moratorium was a difficult one. It was not until a special meeting of the IWC in December 1977, that the United States was given an opportunity to reopen the issue of the bowhead whale hunt. Eskimo participation was obtained in developing a management proposal for submission to the IWC. This plan allowed a limited hunt with quotas on numbers struck, as well as landed, and promised to increase significantly the level of research undertaken. The IWC's Scientific Committee reviewed the U.S. proposal and reiterated its findings that on biological grounds the hunt should not occur. The Scientific Committee also recognized, however, that the IWC might wish to consider subsistence or cultural needs which were beyond the expertise of the Scientific Committee.

Quota Replaces Ban

The IWC did consider these other aspects and finally agreed to remove the ban and allow a take in 1978 of 12 whales landed or 18 whales struck, whichever came first. This quota was lower than the Eskimos had hoped for. At a meeting in Barrow in January of 1978, the AEWC voted to abide by the quota, provided that 1) the AEWC be invited to participate in formation of IWC regulations, both locally and at the international level, 2) the federal government undertake research on methods to reduce the loss of struck whales and on alternate food sources, and 3) Washington commit itself to negotiate for restoration of the subsistence harvest. The IWC and the U.S. government agreed to meet these conditions.

The IWC now had to deal with a very big problem that they had previously avoided. The accuracy of the bowhead whale population estimates that the Scientific Committee had used in developing its recommended moratorium on the Eskimo hunt was in question.

Most bowhead field studies had been limited to observations on migrating whales during the Eskimo harvest. The assumptions that had been made, in these studies, were that all whales migrate past the



The spring migration route of the Western Arctic stock of the bowhead whale.

observation points during this fixed time period, and that all passing whales were then seen by the observers. There is mounting evidence, however, that many whales migrate offshore—out of sight of observers. More comprehensive research efforts are now providing what some consider more accurate information.

In July of 1978, at the IWC meeting, the United States put forward specific proposals for future action, including a catch limit of 30 whales a year, coupled with continued research. Based on a higher, but still low, population estimate of 2,260 whales off the Alaskan coast, the IWC rejected this proposal and voted instead to grant the Eskimos a limit of 18 whales landed or 27 whales struck.

The Eskimos were not satisfied with this decision and walked out of the meeting, informing the IWC that the commission's decision would not affect their hunt of the bowhead whale. The AEWC instead adopted a management plan of its own.

The Technical Committee

At the same time, the IWC began to realize that their decision-making had depended solely on the recommendations of the Scientific Committee. The commission recognized that other factors had to be considered, such as nutritional, cultural, economic, political, and technical goals. Therefore, the IWC created a special working group of the Technical Committee, ". . . to examine the entire aboriginal whaling problem and develop proposals for a regime for the aboriginal bowhead hunt in Alaska and, if appropriate, a regime or regimes for other aboriginal hunts." The working group was given one year to collect data, which was then to be submitted at the IWC's annual meeting on July 1979.

The overall conclusions of the Technical Committee were: 1) on biological grounds, no Bering Sea bowhead whales should be hunted if the population is to have the best chances of recovery; 2) there are a number of alternate sea mammal and other wildlife resources (for example, seals, walruses, birds, and fish) available to replace the bowhead whale in the lives of the northern Alaskan Eskimos; 3) assuming the replacement with foods of equivalent nutritional value, the diet of the Eskimos would not be adversely affected by the removal of the bowhead whale; and 4) change would certainly have a significant impact on the culture of these whaling communities.

With the election of the Reagan Administration in 1980 the U.S. government and Eskimo whalers began to work at settling their differences. As a result, at the 1980 annual meeting of the IWC, the United States presented two reports. One report contained data from the U.S. research program up to June 1980. The other discussed the historical, cultural, and nutritional aspects of the bowhead fishery.

The first report was carefully examined by a special subcommittee of the Scientific Committee. The committee noted with concern that the 1980 quota had been exceeded by five animals. The 1980 census results were considered to be far more reliable than those of 1979 because of better observer coverage during the main migration period. However, many scientists still believe that the best census results were taken in 1978. The 1980 estimate was 1,643 whales with a range of 1,483–1,786.

The second report was submitted to the Technical Committee. It attempted to quantify the needs of the Eskimos in terms of whales landed based on the historical, cultural, and nutritional aspects of the bowhead fishery. It stated that the cultural need had the greatest significance to the community. It proposed a catch limit of 18 whales landed or 26 whales struck. This proposal was defeated. After much discussion, a final catch limit for the three years (1981–1983) of 45 whales landed and 65 whales struck, provided that in any one year the number of whales landed should not exceed 17. This proposal was adopted.

A Satisfactory Resolution

In 1984, the size of the Western Arctic Stock of bowheads was estimated to be 3,871 animals. As a result of this higher estimate, the strike limit for 1984 and 1985 was set at 43, with a maximum of 27 strikes permitted in either year.

Currently, the bowhead whale population in the Western Arctic, is estimated to be 4,417 animals. This higher estimate has been derived primarily from the 1978 data base, since many scientists believe that the 1978 census was the best. However, Mary Nerini, a biologist at the National Marine Mammal Laboratory in Seattle, Washington, believes that the statistical methods used to analyze the data have become so refined that the census estimate truly reflects the bowhead whale population in the Western Arctic. Based on these findings, the U.S. delegation to the IWC, at the July 1985 meeting, sought a quota of 35 strikes for the 1986 season. From these strikes, it was hoped that 26 whales could be landed, a goal based on the increasing success of Eskimo hunters in landing what they strike. However, both the Scientific Committee and the Technical Committee of the IWC maintained that the population is still very low and that the quota should remain unchanged from that of the last year. After a long, heated debate, an agreement emerged which gave the Eskimos a quota of 26 strikes per year for 1985, 1986, and 1987, provided that no more than 32 strikes occur in any one year and that unused strikes could be carried over from one year to the next. As of December 15, 1985, information that is now being used by the United States to prepare for negotiations with the AEWC and IWC have been made available to the public for comment.

To ensure the continued existence of the bowhead whale and the cultural survival of the Alaskan Eskimo, the combined efforts of the Eskimos, U.S. government and IWC are essential and must be maintained. Just as the scientific community and legislators must learn to understand the full importance of the bowhead hunt to the Alaskan Eskimo, so too must the Eskimo begin to appreciate the positions of scientists and lawmakers. For without the complete cooperation of each of these three groups, the ultimate goal of survival for both the bowhead whale and Eskimo culture can never be realized.

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Acknowledgments:

Special thanks to Susan Peterson for her encouragement and support.

profile

Judith McDowell Capuzzo

Portrait by Dorothy Meinert

Educating the Guessers

by Frank Lowenstein

Most oceanographers steer clear of the controversies that surround polluted waters, preferring the clear horizons of the open ocean. But Judith McDowell Capuzzo finds the effects of pollution on organisms fascinating. She also is interested in the complex public-policy issues that accompany such problems. Thus, when the harbor of New Bedford, Massachusetts, was closed to fishing and shellfishing in 1979 because of high levels of polychlorinated biphenyls (PCBs), Capuzzo dived right in.

Since the 1940s approximately 2 million pounds of these toxic chemicals have entered the harbor from leaky landfills and unregulated industrial discharges. Most of the PCBs are now found in the sediment on the bottom of the harbor, and one plan to get rid of them would involve removing the top foot or two of sediment and transporting it to a disposal site, somewhere. Naturally, the question of who is responsible for the pollution—and hence, who should pay for cleaning it up—has generated many lawsuits. The situation is further complicated by the other pollutants in the harbor: petroleum compounds from shipping and urban runoff, heavy metals from industrial operations, and sewage pollution from the city itself.

Meanwhile, Capuzzo, an Associate Scientist in the Biology Department at the Woods Hole Oceanographic Institution (WHOI), finds the harbor a rewarding site for studying marine pollution, and the results of her several research projects around the harbor may influence both future policy decisions and the outcome of the present lawsuits. One of Capuzzo's particular interests has been the effects of pollution at levels lower than those that cause massive die-offs of fish and other organisms. "I'd like to see more rational decisions being made before an area has deteriorated, rather than after the fact," she explains.

Last December, this writer accompanied two of Capuzzo's research assistants to Tin Can Island on the shore of New Bedford Harbor in order to get a first hand sense of Capuzzo's research techniques. It was a cold but sunny day when we pulled into the somewhat incongruous entrance to the research site—a graveyard. After driving through the cemetery, we bounced through some low, ragged dunes, to a brownish beach littered with tires, glass, pipe, and various unidentifiable bits of trash. Looking across the smooth, sunny water to the New Bedford side, Dale Leavitt, one of Capuzzo's two research assistants, mused, "Forty years ago, they used to swim on this beach." Then he turned back to the plastic fish box that held his research equipment.

Within a few minutes, he was shoving clams down into the cold, sandy mud. Occasionally he turned and rinsed his hands in the water trapped by a nearby tire when the tide receded. A few steps away, Bruce Lancaster, Capuzzo's other research assistant, used a clam rake to pick up chunks of mud, then washed them through a screen.

For Capuzzo, how organisms adapt or why some are more sensitive than others is what seems truly interesting.

In other circumstances, he might have been panning for gold, but actually, he is searching for evidence of the effects of pollution. After washing away the mud, he carefully picked through the glass and dead shellfish that remained, looking for living specimens of *Mya arenaria*, the soft shell clam. By comparing the growth rates of clams from Tin Can Island with those of clams from unpolluted sites, Leavitt and Lancaster hope eventually to gain some insights into the effects of the pollution on the clams. So they come out each month to check on their clams. This is field biology at perhaps its least glamorous, although Leavitt is careful to point out that at times it gets worse: in February, for example, they often must break through the ice to get at the clams. Capuzzo herself only occasionally finds the time to accompany her assistants, tending instead to pursue her research in the quiet and somewhat warmer spaces of her office and laboratory at WHOI.

Like much of Capuzzo's research, Leavitt and Lancaster's work on Tin Can Island verges on the realm of public policy. This is a position that most scientists would rather avoid, but Capuzzo regards them as an important aspect of her work.

"One thing that policymakers always criticize scientists for," explains Capuzzo, "is, 'You always tell us we need more information.' And we do! But if a decision is going to be made by a politician, I think that science has a responsibility to society to at least ensure that the best educated guess be made." This commitment to ensuring good public policy involves taking on a variety of tasks not relished by many scientists.

Besides running an active lab, Capuzzo serves on the GEEP (Group of Experts on the Effects of Pollutants) panel of the International Oceanographic Commission of UNESCO, the National Academy of Sciences (NAS) Ocean Studies Board, and the Commonwealth of Massachusetts Marine Fisheries Advisory Commission. She also has chaired panels on biological effects of pollutants at two NAS workshops. More directly, much of her research has looked at the effects of pollutants on the physiology of marine organisms. In a sense Capuzzo bridges what often seems an insurmountable gap in science, the distinction between applied and basic research.

On the Fringe

Even as a graduate student at the University of New Hampshire, Capuzzo's willingness to look at the implications of her research separated her from other graduate students. While there, she worked under John Sasner, a comparative physiologist, from whom she learned to combine laboratory and field work to get a broad view of the problems she was working on. It was there that she developed her commitment to applying "the fundamental rigor of basic research to addressing applied problems," which has repeatedly created problems for her, as scientists are sometimes as eager to draw lines as anyone else.

"Applied people would look at me as applied," she recalls, "but they're interested in the numbers that you generate." Taking oil pollution as an example, Capuzzo explains, "They wouldn't necessarily be interested in the fundamental mechanisms, or how you went about designing an experiment to provide you with a basic understanding of how organisms adapt, in addition to how they respond to oil." For Capuzzo, on the other hand, how organisms adapt or why some are more sensitive than others is what seems truly interesting. This emphasis threw her back into the arena of basic research, but she still didn't quite fit in.

"If I was only looking at development rates of early life history stages, that would be fine, but to add on the impact of oil . . . ." Her voice tails off into a shrug, encompassing the opposition that met her interest in applied problems both at graduate school and after she came to WHOI in 1975. "At many places along the way, people would advise me, 'Well, maybe you shouldn't pursue that area.' But I was dedicated to understanding toxicological mechanisms and thought that I could make an impact. My greatest struggle of the past 12 or 15 years was to continue doing that and keep convincing people that everything else I was doing was important basic research, and the applied aspects of my work were just another component of basic research."

This blend of basic and applied research has proven successful for Capuzzo, bringing her tenure at WHOI in 1984, and the respect of many of her colleagues. As John Farrington, a senior scientist in WHOI's Chemistry Department and Director of the Coastal Research Center, puts it, "I think one of her most outstanding attributes is to undertake research that she thinks is important, despite comments by some colleagues who are more comfortable with 'basic' research."

Capuzzo herself is careful to note that she does a significant amount of straightforward basic research as well, including work on nutrition of early life stages of marine invertebrates and fishes, and on the reproductive cycles of marine animals. In addition, Capuzzo must deal with the administrative responsibilities of running an active lab. As Lancaster notes, "Just getting money and such is pretty much a full time job."

"She is one of the more dedicated people working in education within the biological oceanography department."

Eight Days a Week

To fit in administering her lab, participating in public policy, and doing her own research, Capuzzo often ends up working 20 hour days. "I do a lot of things in a day," she notes, "but I'm very energetic. I guess I won't always be, and so I feel that at this stage in my life, anyway, I can put a lot of energy into these things I think are important."

As a result of her large output of work and her political visibility, Capuzzo's recognition as a scientist already exceeds that of most researchers of comparable age. "There's no question," explains Farrington, "that she's highly respected nationally and internationally for her work on aquatic marine organisms." At one recent meeting, Capuzzo recalls being told by a scientist whom she had not previously met, "You know, Judy, I thought you were going to be about 50 years old."

The 38-year-old Capuzzo, whose usually tousled, red hair makes her look considerably younger, does admit to "being a real workaholic at times. I hope that through my efforts now, policy decisions would be better over the next five years. Maybe in 10 years I'll be working on better housing for the elderly or new pharmaceuticals from marine species or something like that."

Over the last five years, Capuzzo has gradually taken on more and more responsibilities outside of her research, which recently have brought her recognition outside of science. In its September 1985 issue, *New England Monthly* included Capuzzo as one of its 59 Local Heroes—for her work in studying "the effects of humans on marine life . . . and how those effects can be minimized or prevented."

Early Roots

Capuzzo attributes her original interest in marine science in large part to her mother, Catherine Sullivan McDowell. "My mom trained as a zoologist. She went to the University of New Hampshire, and she studied on the Isles of Shoals. They had a marine lab there in the late '30s. She always talked about how neat it was to be out there; fishermen would come on shore with their short lobsters and you would buy them for 10 cents apiece and cook them over a fire in the evening."

Although Capuzzo's mother did not pursue this interest in marine biology professionally (she became a schoolteacher in rural New Hampshire), Capuzzo recalls that her mother "always maintained an interest. Not really a scientific interest, but a love of nature. She stayed in New Hampshire, married my dad [Joseph F. McDowell, a New Yorker who grew up in the Bronx], and lived in the house she grew up in. And we always went to the ocean—to the New Hampshire shore—in the summertime, and I spent these long days walking up and down the beaches. We'd sit around the beach and she'd talk about her days on the Isles of Shoals. It always inspired me and excited me." Capuzzo now enjoys sharing this same enthusiasm for the sea with a younger generation of nephews and friends.

Capuzzo grew up in New Hampshire with her parents, her younger sister (Cathy McDowell), and her older brother (Joseph McDowell). Cathy is now Assistant Director of the American Cancer Society in the Worcester area. Joseph is a lawyer, and like their parents he lives in New Hampshire. Capuzzo's father, now retired, was formerly a commercial artist working in advertising, and it is to him that Capuzzo traces many of her creative interests.

Among these she counts knitting, gardening, and weaving. To pursue these interests Capuzzo maintains a greenhouse, where she grows a variety of plants in order to have some in bloom for most of the year. She also owns three small looms and one larger loom. "I really wanted to be a fashion designer," she muses. But, she notes with a wistful shake of her head, "I'm not that talented. I'd be a pauper. But I really wanted to do something artistic." In high school, she was shy, retiring and good at science and math. It was these talents that she eventually chose to follow.

Nowadays, Capuzzo releases her creativity into her science, designing what are generally seen as elegant experiments. Still, she worries "that people will only remember me as a scientist." She hesitates for a moment and then continues, "I mean I like being remembered as a scientist, but I like having other interests as well."

Students and the Future

Along with politics and research, Capuzzo also has a reputation for taking a great interest in students. "She is one of the more dedicated people working in education within the biological oceanography department," explains Farrington. Capuzzo's research assistant Dale Leavitt puts it a little differently: "Judy picks up a lot of wayward students; she's a soft touch. If anybody's got a problem they usually end up on her doorstep." As for Capuzzo herself, she likes working with students, be they interns, undergraduates, or graduate students. Until this year she taught oceanography at Bridgewater State College, and she advises and supervises the work of many graduate students and interns at WHOI. Capuzzo explains, "It's neat to see them grasp onto a problem and take it to completion and sit back and think, 'Wow! I really did something.'"

"She's a role model for both men and women in the realm of public policy and applied problems."

According to Patricia Biesiot, one of Capuzzo's advisees in the Massachusetts Institute of Technology/WHOI joint graduate program in oceanography, Capuzzo's enthusiasm really helps. "She just thinks you can do it, and because she thinks you can, you can," Biesiot explains. "She doesn't seem like a really dynamic person; she's low-keyed and quiet. But she's really sharp. I don't think I could ever emulate her, but I've tried to be a better scientist because of her."

When Biesiot first arrived at WHOI in 1980, it was the summer of WHOI's 50th anniversary year and a special graduation ceremony for joint program students was underway. "Judy was in the procession," Biesiot recalls, "wearing a cap and gown, holding a staff, her hair flying in the wind." In these somewhat intimidating circumstances Biesiot approached Capuzzo, who had been assigned as her initial adviser and was met with perhaps unexpected friendliness: "She said, 'Oh! my new student!' and then she took me around and introduced me to everyone."

Over time, Capuzzo became something of a role model for Biesiot. "She's the only tenured woman scientist at WHOI," Biesiot explains. "There just aren't very many women who are in that position. She's a role model for both men and women in the realms of public policy and applied problems, but especially for women." Capuzzo talks often to both high school and college audiences about women in science, according to Biesiot.

In addition to her work with students, her involvement in public policy, and her present research, Capuzzo looks forward to future possibilities. One of the many topics that she is interested in investigating is the role of natural toxins in ecological relationships. In a sense, such research is an extension of Capuzzo's earlier work on man-made toxins and marine ecosystems. The natural toxins she will be looking at are produced and stored by both animals and plants to deter other animals from eating them. Such interactions are well-documented in terrestrial ecosystems, but there has been little research on marine counterparts. Natural marine toxins, Capuzzo believes, might have uses as drugs or pesticides, and in any case would shed new light on the structure of marine ecosystems. Capuzzo is also working on mariculture, and hopes to look at detailed biochemical aspects of molting in crustaceans.

As Biesiot sees it, "Judy's a perfect example of that old saying, 'If you want something to get done, get a busy person to do it.'"

cruise report

First Argo Scientific Test Yields Unexpected Ridge Data

by Sarah A. Little

A multi-institutional, international collection of scientists recently returned from the first scientific field trials of the *Argo* televiewer system which was designed and built for surveying the seafloor. The specific objectives of the *ArgoRise* cruise to the East Pacific Rise off Mexico were to investigate the volcanism, tectonics, and the hydrothermal activity of the active spreading ridge axis between the Pacific and Cocos plates. Included on the expedition were a number of observers (Bill Schwab [U.S. Geological Survey], Helge Trygg-Anderson [Norway], and Chris Williams [U.S. Navy]), who wished to learn about the capabilities of the *Argo* system and test its scientific potential. In addition, the unique capabilities of real-time data transmission allowed several other experiments to be conducted, such as a temperature survey, acoustic detection of hydrothermal vents, and a biological assessment of hydrothermal vent fauna both along and across the spreading ridge axis. *Argo* is the unmanned submersible system that discovered the *Titanic*, (see *Oceanus*, Vol. 28, No. 4) in September of 1985, in its first checkout trial.

The main geologic impetus of the *ArgoRise* project was to test and develop geophysical models which predict physical characteristics, such as hydrothermal circulation, tectonic faulting, and magmatic activity from surface morphology and topography at Mid-Ocean Ridges. In particular, the scientists (Robert Ballard [Woods Hole Oceanographic Institution], Jean Francheteau [Institute de Physique du Globe (IPG)], Roger Hekinian [Institut Français de Recherche Pour l'Exploitation des Mers], Jean-Louis Cheminee [IPG], and Haraldur Sigurdsson [University of Rhode Island]) sought to support or refute the hypothesis that axial topographic highs are formed over sites of recent magma injections and, as a result, are the sites of copious surface-fed fluid lavas (Ballard and others, 1979), few open fissures or faults, and high levels of hydrothermal heat flow. Conversely, axial topographic lows should be characterized by tube fed pillow lavas, much faulting and fissuring, and little or no hydrothermal activity.

The cruise plan called for starting the seafloor survey at the site of a discontinuity in the ridge axis: a ridge offset located at 12 degrees North, and then travelling south toward the Clipperton fracture zone at 10 degrees North. Four sites, each approximately 10 to 15 kilometers long, were chosen for detailed geologic mapping, which required putting in acoustic transponder nets for accurate positioning of both the ship and the *Argo* sled. In between these sites, global positioning satellites were used to locate the ship while the position of the sled was estimated. The four sites studied were: the two ridge terminations at the ridge offset, the southern axial topographic high, and an area of very fresh lava flows south of the axial high (previously explored with the Acoustically Navigated Geophysical Underwater Survey [ANGUS] still camera system). Unexpectedly, the freshest lava flows and the most hydrothermal activity were found south of the axial high rather than right on it. This indicates that the center of magmatic activity may be migrating south and, in any case, the physical processes governing ridge crest surface features are more complex than previously thought.

The subset of experiments conducted on this expedition—the temperature, sound and biology surveys—were smoothly integrated into the *Argo* operations and all three yielded useful information. The temperature survey of the axial valley will allow us to calculate the heat flux from a spreading ridge segment and compare the activity of this section of the East Pacific Rise with other well-studied areas. The acoustic experiment, designed to determine whether or not the hydrothermal vents produce detectable sound, resulted in more than 200 hours of continuous recording of various deep ocean sounds. It is hoped that in the future the vent sound signal can be monitored for a long period of time (months to years) and used to understand the presently unknown life cycles of hydrothermal vents. The equipment for sound detection operated flawlessly and a number of anomalous signals were recorded, although the final conclusions on vent sound will have to wait until all the data are assimilated. The biology survey, conducted by Cindy Van Dover (Marine Biological Laboratory), was undertaken to study the distribution of vent fauna and to determine the dispersal mechanism of the animals and their larvae. Several low-altitude passes were made across and along the ridge to facilitate the identification of the various animals.

The components of the *Argo* system for this cruise included three black and white video cameras (downward looking, wide angle; downward looking zoom; and forward looking), an operator-controlled color still camera (with film developed onboard the ship), two side-scan and one forward-looking sonar (for collision avoidance), a temperature probe, and a hydrophone.

Deployment

The procedure for a deployment began with a checklist to ensure that all electronic systems were operational. The *Argo* sled was then lowered to the bottom on a coaxial conducting cable which transmitted power down to the cameras, and video images back up to the laboratory van, which housed the monitoring equipment. The cable passed from the winch through a heave compensating device which reduced the effect of the ocean waves on the vertical motion of the *Argo* sled. For a typical lowering it took about 1.5 hours to reach the bottom. Once the seafloor was sighted, the driver of the ship proceeded along the axial valley, at a speed of 0.5 knots or less, according to the directions of the scientists. Geologic formations were then mapped onto the navigation chart as they appeared on the video screen. This map was then used to identify areas to which to return for more detailed investigation from minutes to hours later.

The first deployment resulted in more than 70 hours of continuous bottom viewing and data recording. Subsequent to this, the zoom lens failed to operate but this was the only serious casualty of the entire cruise. In all, *Argo* had to be pulled on board 5 times during the 10 days on station, due in part to electronic problems and in part to transiting and transponder emplacement, but the total operating time was greater than 80 percent of the allotted surveying time.

The continuous video monitoring capabilities of *Argo* provided extremely interesting and useful scientific coverage of the seafloor on the axis of the East Pacific Rise. It allowed us to see the different morphologies and lava types in contact with one another and therefore gave a more complete picture of the processes occurring at the spreading center. The downward looking, wide-angle camera on *Argo* gave an image area of 100 to 1,000 square meters, depending on the sled height above bottom (usually from 3 to 10 meters). The images were quite clear and small features could be discerned with the zoom lens. These capabilities made the geologic and biologic mapping straightforward and sufficiently detailed for scientists interested in small-scale processes on the seafloor.

However, it turned out to be difficult to see the black smokers characteristic of active hydrothermal vent sites for two reasons. First, the black smoke against a black background was difficult to pick out using only a black and white video image. Second, the smokers came into the field of view about the same time that the rising smoke obscured the camera's view. The turbidity of the water near vents also forced us to lower the camera and reduce the area of the seafloor that could be seen. The forward-looking camera alleviated some of these problems, but it did not give the detailed plan view that is necessary to map the geologic features of the ocean bottom.

Another difficulty occurred because during this cruise the positioning was done by hand, that is, by controlling the ship from the laboratory van while watching a monitor showing continually updated navigational information. This method was somewhat cumbersome, and although it was possible to return the *Argo* sled to the same spot on the seafloor, wind, waves, and currents coupled with human fallibility often made this a time-consuming task.

These shortcomings of the system had been foreseen, and future improvements planned for *Argo* include a fiber optic cable to permit color video transmission and a computer-operated dynamic positioning system which would allow precise movements of the *Argo* sled. With these improvements, the system will be quite powerful and with the added capability of taking geological, chemical, and biological samples with *Jason* (a smaller robotic vehicle to be remotely operated from *Argo*), it will rival the capabilities of manned submersibles in these respects in addition to being able to use time at sea much more efficiently.

Sarah Little is a doctoral candidate in the WHOI/MIT joint program in oceanography. She conducted the acoustic experiments on the ArgoRise *expedition.*

Cover Credits

Front Cover: Iceberg; Fred Bruemmer, *Arctic World*. Polar bears; Thor Larsen, National Science Foundation. Svalbard coastline; Mitchell Taylor, National Science Foundation. Two Inuit hunters; John Reeves, *Arctic World*. Beluga whales; Fred Bruemmer, *Arctic World*. Walruses on sea ice; Mitchell Taylor, National Science Foundation.
Back Cover: Trans-Alaskan Pipeline, courtesy of the American Petroleum Institute.

To the Editor:

The undersigned are collecting data on:

a) References in the literature to the role (however limited or extensive) of chance in the advance of science, engineering, and technology.

b) Personal experiences of serendipity unrecorded, or incompletely referred to in published papers.

We would be grateful for any well-documented information which readers can supply. Please send such material to the last-named.

Patrick J. Hannan
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To the Editor:

It was gratifying to see "Lord of the Californian," my defense of Captain Stanley Lord of the *S. S. Californian*, in the pages of *Oceanus* (Vol. 28, No. 4). This article was originally published in the U. S. Naval Institute *Proceedings*. I believe my points were made clear in that article and it would only be redundant to enumerate any of the additional information in Captain Lord's favor that has surfaced since the original writing. However, I would like to relate what turned my mind in Captain Lord's direction compelling me to retract what I had previously written about him in the *Proceedings*.

It was while standing on deck of the *S. S. Brasil*, where I was serving as an engineering officer, that it finally dawned on me that Captain Lord was correct in his contention that the *Titanic* lay nearly 20 miles away from the *Californian* while she was sinking and not the 5 to 8 miles claimed by his accusers. This occurred when a large jet aircraft flew over the ship emitting the long white vapor trail associated with high flying aircraft. Obviously the plane was at an altitude of some 40,000 feet or about seven nautical miles. It was then that I asked myself: "If the distance between that plane and me was about the same distance Lord Mersey and Senator Smith claimed was the distance between the two ships during the sinking, then: How come no one on the *Californian* recognized the *Titanic* lit up like a Christmas tree? How come no one on the *Californian* saw the *Titanic*'s powerful blinker light flashing for help? How come no one on the *Titanic* saw the *Californian*'s powerful blinker light asking a ship stopped about four miles away for identification?"

The same issue of *Oceanus* carried Eugene Seder's article, "Gill, the Donkeyman's Tale," an exposé of the affidavit Ernest Gill, the *Californian*'s donkeyman, sold to a Boston newspaper. It was this affidavit, and this affidavit alone, that brought forth the condemnation of Captain Lord which continues to this day.

Gill's story began when, having been trapped all night in a heavy icepack, the *Californian* got under way shortly after daybreak. She had received word of the *Titanic*'s plight about three hours after the sinking and immediately headed for the distress position. When word of the sinking plus the fact that rockets had been observed from the bridge during the night made their way throughout the ship, rumors spread like wildfire. The seafaring man has never been known to spoil a good story with the truth and by the time the ship reached Boston, Gill was telling a story created from hearsay and imagination which, by then, he most probably believed himself. What the newspaper thought of Gill's sensational story is of no consequence. What is highly significant however is that the newspaper required the story to be in affidavit form before publishing it and paying Gill $500.

In preparing the affidavit Gill's problem was to produce a plausible reason for his being on the open deck in freezing temperature where he allegedly watched the *Titanic*'s rockets. Here the affidavit read: "I turned in, but could not sleep. In half an hour I turned out, thinking to smoke a cigarette. Because of the cargo I could not smoke 'tween decks, so I went on deck again." He had crossed the open deck at midnight en route to his quarters in the fo'c'sle from the engine room. It was then that he allegedly saw the *Titanic* at a distance of 10 miles running at full speed. (No one else saw this ship.)

Any seafaring person, from apprentice to captain, knows that when smoking is prohibited because of dangerous cargoes, the quarters (where Gill was in bed) are the last and usually the only place where smoking would be permitted. At the same time the open deck where Gill allegedly went to smoke is without exception the very first place to be declared "off limits" for smoking because of dangerous cargoes. A live spark finding its way down a ventilator shaft into the cargo could spell instant disaster.

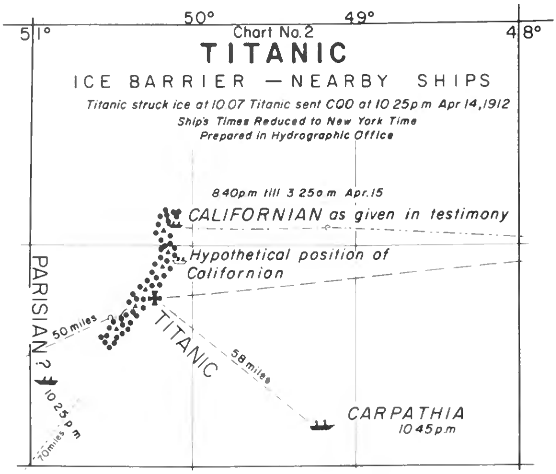
As a result of the publishing of this affidavit Gill, Captain Lord, and Cyril Evans, the *Californian*'s Marconi operator, were summoned to Washington to testify before Senator Smith's committee investigating the disaster. At the hearings Senator Smith read the affidavit aloud to Gill asking him if it were the truth. Under oath Gill replied, "Yes sir; that is correct." Gill's time spent on the witness stand at both the British and American investigations was short lived. Nevertheless, from his affidavit and testimony we find that, dressed in his linens (underwear), he remained on the open deck for more than 15 minutes smoking cigarettes as he watched rockets being fired by the *Titanic*, which he could no longer see! Captain John J. Knapp, USN, the Navy's chief hydrographer, served as Senator Smith's nautical adviser throughout the investigation. Why he permitted Gill's perjury to remain unchallenged will always remain a mystery.

The following is taken from Captain Rostron's testimony at the congressional investigation telling the conditions in the area while the *Carpathia* was picking up the *Titanic*'s survivors.

"I also saw icebergs all around me. There were about 20 icebergs that would be anywhere from about 150 to 200 feet high and numerous smaller bergs; also numerous were what we call 'growlers'. You would not call them bergs. They were anywhere from 10 to 12 feet high and 10 to 15 feet long above the water."

At Lord Mersey's investigation Captain Rostron said: "I sent a junior officer to the top of the wheelhouse, and told him to count the icebergs 150 to 200 feet high: I sampled out one or two and told him to count the icebergs of about that size. He counted 25 large ones, 150 to 200 feet high, and stopped counting the smaller ones; there were dozens and dozens all over the place; and about two or three miles from the *Titanic*'s wreckage we saw a huge ice field extending as far as we could see N.W. to S.E."

With all this information available how could Senator Smith and Lord Mersey include the following in their summations?



This is a copy of one of the three plots of the disaster area prepared by Captain John J. Knapp, USN, for Senator Smith's congressional investigation. The three are contained with the full text of the testimony published after the inquiry. They were prepared from the ice reports submitted by several of the ships in the area at the time of the disaster. The dots represent heavy pack ice and growlers. The triangles represent icebergs.

Senator Smith:

"I call attention to the fact that from the chart (see plot) you can readily see the position of the *Californian*, and that to the eastward there is no ice, to the southward of her there is no ice, and to the northward there is no ice; this ship was not surrounded by ice. She was against the ice in her westward course, and was in exactly the same situation as the *Titanic* before the impact."

Lord Mersey:

"The ice by which the *Californian* was surrounded was loose ice extending for a distance of not more than two or three miles in the direction of the *Titanic*. The night was clear and the sea was smooth. When she first saw the rockets the *Californian* could have pushed through the ice to the open water without serious risk and so have come to the assistance of the *Titanic*. Had she done so she might have saved many if not all the lives that were lost."

The condemnation of Captain Lord petered out at the start of World War I in 1914. It remained more or less dormant for nearly fifty years when in 1959 it was again emphatically mentioned by Walter Lord in his best seller, *A Night to Remember*. Time and again the myth has been expanded by authors who still find the subject fascinating and it has become difficult to separate fact from fancy. This was demonstrated by Dr. Ballard who discovered the *Titanic*'s remains at his National Geographic press conference in Washington and in *Oceanus*, where he is quoted as saying, "We had to assume that the data from the *Californian* had either been altered, collected poorly, or something—we could not believe it."

John C. Carrothers
Deep River, Connecticut

To the Editor:

I have read the *Titanic* issue of Oceanus with great interest and enjoyment. I would, however, like to call your attention to the fact that the *QE II* is not the largest passenger (pax) vessel currently in operation. This distinction must unquestionably go to the *Norway*.

The popular measurement is length, and at 1,035 feet *Norway* is 72 feet longer than *QE II*. It is interesting to note that there have only been four pax vessels constructed over 1,000 feet. The first, and many feel the grandest of these ships, was *Normandie*. She was 1,028 feet long and made her maiden voyage in 1935. She was followed in 1936 by the *Queen Mary* at 1,017 feet, and in 1940 by the *Queen Elizabeth* at 1,031 feet. In 1962 the *France* made her first crossing, thus becoming the longest vessel by 4 feet. Now renamed *Norway* she is operated principally, but not exclusively, in the Caribbean by the Norwegian Caribbean Line.

I think a more realistic judge of size would be Displacement Tonnage, but here I have not been able to find complete figures. The various books I have compared do not agree, and the tonnage quoted frequently has no designation which makes the figures meaningless. But at 72 feet longer and only 5 feet less beam I would guess *Norway*'s Displacement Tonnage is greater than that of *QE II*.

I have been able to compare the Gross Tonnage of the two vessels. Since they are in the same service I think G.T. is a fair method of comparison. *QE II* measures 65,863 G.T., while *Norway* is 70,202 G.T.

I remember an evening of exploring *Norway*'s interior. On one of the lower pax accommodation decks I found a unique passageway in that it had no jogs or turns. This allowed me to see from one end to the other, and because of the vessel's sheer the white jacketed steward standing at the far end was cut off at the chest by the overhead. I paced off the length: it was 250 yards long!

Courtenay Barber, III
Relief Mate, R/V ATLANTIS II,
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

Editor's Note: Right you are. We got caught between conversions.

To the Editor:

The caption of the photograph on page 10 of the Winter 1984/85 issue of *Oceanus* incorrectly identifies the vessel involved with the platform collision as a fishing vessel. It is of course an oilfield supply boat, owned and operated at the time by State Boat Company.

The fact that the vessel in question is an oilfield boat instead of a fishing vessel does not change or diminish the fact that accidents can occur. However, the implication that platforms and drilling vessels are a hazard to navigation, an allegation often put forth by opponents of offshore oil development, is erroneous. The U.S. Coast Guard identifies platforms and rigs as *aids to navigation*. While freak accidents can happen in any industry they are no more prevalent in the offshore oil industry than in any other ocean oriented endeavor.

The accident pictured was not a case of a hazard to navigation but instead a lack of navigation . . . the operator fell asleep at the helm and *no* injuries occurred.

Finally, I am frankly surprised that an ocean-use oriented magazine staff did not recognize the difference between the two types of vessels or at least do enough research to get the facts rather than make assumptions.

The offshore oil industry has enough dragons to slay and myths to dispell without respected publications adding to the wealth of misinformation already afoot.

Carroll Hill
Vice President
Richill Marine, Inc.
Ventura, Calif.

EDITOR'S NOTE: The vessel was incorrectly identified. *Oceanus* regrets the error.

To the Editor:

A scientist at the Woods Hole Oceanographic Institution involved in Arctic Research questioned a reference in my article in the Oceans and National Security issue (Vol. 28, No. 2) to Russians in and near Svalbard (page 65): "Any possibility, however remote, of a Soviet presence in these lands—including Svalbard—is unthinkable."

My wording was misleading. There is, of course, a sizeable Russian population already there, ostensibly mainly in mining. I intended to make clear that an *increased* Soviet presence in Svalbard relating to defense would (or should) be unthinkable.

Melvin A. Conant,
President,
Conant and Associates, Ltd.,
Great Falls, Virginia

To the Editor:

This is to commend *Oceanus* for Sara Ellis's "Concerns" article on the whaling issue [Vol. 28, No. 3]. It is timely and informative, but it also contains some important inaccuracies which have been the subject of much controversy within the International Whaling Commission (IWC). I would not like to detract from her otherwise good article by discussing details because of space constraints in attempting to elaborate on complex issues and their implications.

The central point that must be addressed here is the precedent of the negotiation of a bilateral agreement between the United States and Japan, two IWC members, on matters that have been examined, discussed, voted upon, and adopted by the IWC. The agreement sets a most unfortunate precedent because it allows the U.S. government, which has followed one policy within the international forum, to contradict its policy and undermine the legal and orderly operation of the forum itself. The issue is particularly serious when the negotiations involved the 'acceptance' of catch quotas which were not approved by the IWC, which have no scientific basis, and which permit the killing of sperm whales (a species regarded by U.S. domestic law and international law—the CITES Convention—as an endangered species). The bilateral agreement has been challenged in U.S. courts by a number of conservationist organizations. The courts have ruled in two instances that the Administration does not have discretionary power in applying existing and pertinent laws and thus must sanction the Japanese whalers who have diminished the effectiveness of the management decisions adopted by the IWC. The case has been taken to the Supreme Court and a final decision is expected before March.

Finally, it is most difficult to understand how a government that has explicitly sought the end of commercial whaling for over a decade, is now a partner of the Japanese whaling industry in challenging the legislative branch by not applying (or applying selectively) pertinent laws. Such ambiguous policy permits the continuation of commercial whaling (despite the phase-out period included in the IWC 1982 decision for a pause in commercial whaling).

Furthermore, the bilateral agreements disregard and undermine the views of the majority of IWC member nations and the decisions they adopt (with U.S. support and leadership) within the IWC. It is now clear that inertia in using the most important leverage available to force the compliance with IWC decisions opens the door for other governments like the Philippines, Iceland, and South Korea to continue commercial whaling disregarding international law; others will probably follow.

The effective protection of whales has not been achieved despite enormous efforts by many people, organizations, and governments. If the future remains uncertain for whales, what hope is there for other endangered species, ourselves, the biosphere?

Francisco J. Palacio
Comissioner for Saint Lucia
International Whaling Commission
Miami, Florida

To the Editor:

The memories of the sinking of the *Titanic* have been with me most of my life. My father, author Jacques Futrelle, was among the victims. My mother, May Futrelle, also an author, survived to live out, from time to time, the sheer terror of the experience. My father was 37. My mother lived to be 90.

It is my earnest prayer that the *Titanic* be allowed to remain where she lies. It seems only honorable and respectful to leave the ship and its victims in their final resting place as was God's will.

I fail to see any valid reason for raising the liner other than personal exploitation for those undertaking the task.

Why not let those who died so gallantly lie undisturbed in their eternal slumber.

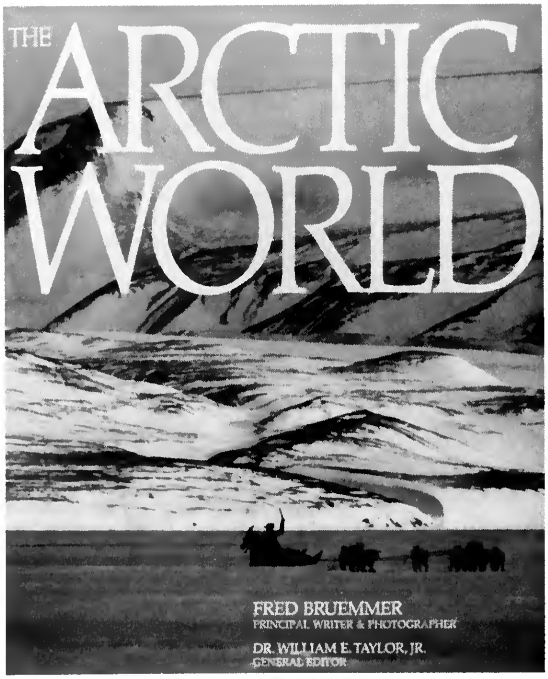
I have always thought of the *Titanic* as my father's grave. For years my mother tossed flowers on the Atlantic on the anniversary of the disaster, honoring my father and all those who died with him.

The *Titanic* at rest is a memorial in itself. Please, let her be.

Virginia F. Raymond
Scituate, Massachusetts

book reviews

The Arctic World **by Fred Bruemmer (principal writer and photographer). 1985. Sierra Club Books, San Francisco, CA. Published in Canada by Key Porter Books, Toronto. 256 pp. $39.95.**



The majesty of a lone polar bear; the lore of caribou hunters and reindeer herders; the misadventures of explorers; and the integration of modern culture with a traditionally nomadic lifestyle: these stories and more are told through a fascinating kaleidoscope of pictorial essays and narration. The 130 color and 100 black-and-white photographs leave the reader marvelling at the space and beauty of a land few will actually visit. The reader can easily become spellbound by the pictures, and may be drawn through the book by the desire to see if the next pictures are as magnificent as the preceding ones.

Once the reader pulls away from the photography, he will be greeted by well-written text. The authors, including an anthropologist, a botanist, an archaeologist, and a 20-year arctic expert, all write in clear, enjoyable prose that not only makes their specialty interesting, but also blends in with the overall narrative tone of the book. The history of this region, both in terms of exploration and archaeology, the features of this unique environment, and the ways man, flora, and fauna have adapted to the severe cold thus come alive in the presentation.

The discovery of the Arctic is chronicled through anecdotes of explorers from the Soviet Union, Britain, the Netherlands, and other nations. These adventurers came searching for the Northwest Passage, the North Pole, and riches—fur, ivory, and minerals. Quotations from these adventurers enliven the first part of this historical narration, adding local color and allowing the reader to share each explorer's sense of wonder about this frigid environment. Illustrations of actual expeditions turn the reader's imagination back to the centuries when this region was still an uncharted region on the map, into which no one had safely ventured.

As good as it is, this book does have at least one fault. After several chapters on early exploration, a later review chapter entitled polar exploration seems repetitious. And perhaps the book could have explored the once self-sufficient lifestyles of native arctic dwellers, with their dogsleds, tents, igloos, and strong family ties, or profiled the rapidly disappearing traditions of the older generations. The intimate photographs of people at work, in celebration, and with families left this reader hungry for more details about these people.

A section on the early Paleoeskimos explains the archaeology from the last European ice age 25,000 to 12,000 years ago up until the Little Ice Age of the 1600s. This informative silhouette of the cultures of these ancient tribes fosters an aura of mystery surrounding both past and present arctic life. This reader, her curiosity raised, was unfortunately left wondering how to complete the picture of life between the 1600s and today.

This book will appeal to a variety of readers—from the serious arctic fanatic to the casual coffee-table reader. Experts will enjoy the light but accurate treatment of the Arctic; and coffee-table readers will eagerly return again and again to this largely picture book. The real point of this book is the exquisite photographs—landscapes of the sea and mountains; abstract shapes of ice and snow; and the daily activities of both man and animals. The photographs are a permanent testimony to a changing world, a world no longer isolated or safe from modernization.

Eleanore Scavotto
Editorial Assistant, Oceanus

Outlaws of the Ocean **by G. O. W. Muller and Freda Adler. 1985. Hearst Marine Books, New York, NY. 362 pp. $17.95**

Professors Mueller and Adler have performed a very complete and timely documentation of a wide range of unlawful activity taking place on the world's waterways. From drug smuggling to piracy, from terrorism to main insurance fraud, the authors have gathered a veritable treasure trove of source material. The book is written in an easy going, accessible manner, which should appeal to the serious scholar and the armchair oceanfarer alike.

As an introduction to the individual issues discussed, this book is invaluable. It is less useful, however, if the reader seeks to understand why each problem persists and what, if anything, can be done to stop the various outlaws of the ocean. For example, in response to the enormous problem of ship scuttling and other marine insurance frauds, the authors recite, without detail, the current notion of a computerized, universal registry of shipping and maritime transactions. Sounds good. What they failed to mention is that incredible resistance to this idea by the international banking and other sectors which fear the additional responsibilities and liabilities that would be placed upon them under the registry proposal. Similarly, in response to the growing problem of piracy and maritime violence, the authors call for an "international marine patrol." Sounds sensible. Yet the overwhelming majority of violent maritime attacks on cargo and people occur in the territorial waters of sovereign states, which are loathe to all infringement on their jurisdiction.

In sympathy to the authors, it must be admitted that putting a cap on mushrooming international criminality on the oceans or elsewhere is a daunting task that will require rethinking long-cherished principles of sovereignty and jurisdiction. And it will be another decade before concrete steps are taken by nations to inhibit the outlaws of the ocean.

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Marine Policy and Ocean Management Center,
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Books Received

Biology

***Advances in Marine Biology: Volume 22,* J. H. S. Blaxter, Frederick S. Russell, and Maurice Yonge, eds. 1985. Academic Press, Inc., Orlando, FL. 259 pp. + xi. $57.00.**

Scientific articles covering reef corals, sea anemones, bivalve molluscs, and barnacles detail field and laboratory observations and discuss experimental results. The serious marine biologist interested in one of the above topics will find this book informative.

Environment/Ecology

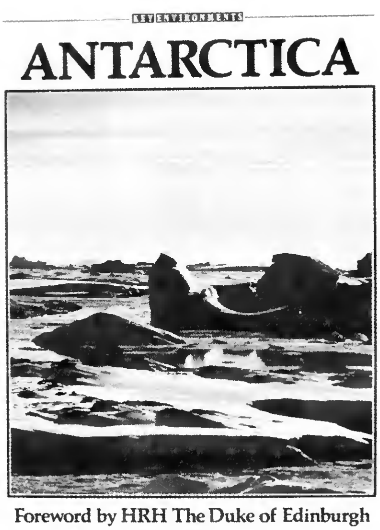
***Algae as Ecological Indicators,* L. Elliot Shubert, ed. 1984. Academic Press, Inc., Orlando, FL. 434 pp. + xii. $65.00.**

Algae are an important link in the food chain and are thus essential to environmental stability. This book provides an integrated account of the research involved in studies on algae as ecological indicators (algal assays) in a variety of experimental situations: freshwater, marine, and terrestrial ecosystems; pollution monitors; and industrial applications. For the serious ecologist.

***Cetacean Behavior: Mechanisms and Functions,* Louis M. Herman, ed. 1980. John Wiley and Sons, Inc. New York, NY. 463 pp. + xi. $42.50.**

Cetaceans—whales, porpoises, and particularly dolphins—are studied in this review intended for a wide readership. Experts examine sensory mechanisms—namely audition and vision—communication's relationship to ecological and social conditions, cetacean schools, behavior training, and cognitive characteristics in captivity.

***Key Environments: Antarctica,* W. N. Bonner and D. W. H. Walton, eds. 1985. Pergamon Press, Elmsford, NY. 381 pp. + x. $23.50.**



Published in collaboration with the International Union for the Conservation of Nature, this book details the unique features of the Antarctic—its physical geology, terrestrial and marine habitats, and its flora and fauna—in a style appropriate for both scientists and lay readers. Scientists describe what is currently known about the antarctic ecosystem, a harsh environment where the sea covers more than twice the area of land. The goal of the book is to provide readers with background information useful when developing conservation strategies.

***The Physiological Ecology of Seaweeds* by Christopher S. Lobban, Paul J. Harrison, and Mary Jo Duncan. 1985. Cambridge University Press, New York, NY. 242 pp. $44.50.**

Discusses physical, chemical, and biological factors that affect the growth and distribution of seaweeds—red, brown, and green marine algae. Intended for advanced undergraduate and graduate courses, the textbook stresses the ways in which seaweed reacts to light and photosynthesis, temperature, salinity, water motion, nutrients, pollution and other environmental elements.

***The Nordic Seas,* Burton G. Hurdle, ed. 1986. Springer-Verlag, New York, NY. 777 pp. + xiii. $69.50.**

A scientific description of the environment of the Norwegian, Greenland, and western Barents Seas—an area collectively called the Nordic Seas. The present status of research and knowledge on the atmosphere, the sea, and the seafloor is discussed in articles ranging from bathymetry to climatology to plate tectonics. More than 250 illustrations, tables, and charts help explain the unique physical properties to scientists, engineers, and anyone else intrigued by these northern seas.

General Reading

Arctic Dreams: Imagination and Desire in a Northern Landscape **by Barry Lopez. 1986. Charles Scribner's and Sons, New York, NY. 464 pp. + xxix. $22.95.**

This factual narration of the Arctic—its land, animals, and explorers—expresses the author's sense of awe and harmony with both the actual and metaphorical presence of the region. The Arctic is a story of "ageless conversation, not only among ourselves..., but a conversation held with the land,"...."a land where airplanes track icebergs the size of Cleveland and polar bears fly down out of the stars." Three themes lie at the heart of this first-person narrative: 1) the influence of the arctic landscape on our imagination; 2) how a desire to put a landscape to use shapes our evaluation of it; and, 3) what happens to our sense of wealth when confronted by an unknown landscape.

Arctic Ocean Engineering for the 21st Century, **Ben C. Gerwick, ed. 1985. Marine Technology Society, Washington, D.C. 234 pp. $30.00.**

The proceedings of the First Spilhaus Symposium, held in Williamsburg, Virginia, October 1984. The volume has five parts: the introduction covers work systems, oil and gas, environmental considerations, transportation, scientific research, minerals, sea-ice management, and materials; the Arctic perspectives section comprises technical presentations made by speakers at the symposium; the workshop reports summarize discussions and conclusions; the plenary papers are further technical works, including a scenario for the 21st century on oil; and the appendices provide further symposium information.

European Vision and the South Pacific **by Bernard Smith. 1985. Yale University Press, New Haven, CT. 370 pp. + xiii. $45.00.**

The European explorers of the late 18th and early 19th centuries, upon discovering the previously unknown lands of the Pacific, revised both their perceptions of evolution and their techniques of painting. The Pacific's evolutionary evidence pitted science against religion (the Biblical theory of creation). The Europeans combined art and science to accurately record what they saw, landscapes as well as natives, in visual documentation of the land and sea. This fully revised and richly illustrated book will delight scientists, artists, historians, and anyone else intrigued by the Pacific.

Islands of the West: From Baja to Vancouver, **photographs by Frans Lanting and text by Page Stegner. 1985. Sierra Club Books, San Francisco, CA. 144 pp. $35.00.**

The 74 color and 22 black-and-white photographs of the islands off the Pacific Coast of North America are carefully woven together with a firsthand, personal narration of the growth, people, and moods of the islands. This book takes the reader on a tour of this beautiful area through pictures and anecdotes which convey both the untamed and the exploited spirit of the west coast.

Vol 26:4, Winter 1983/84

- **Offshore Oil and Gas,**
Vol 26:3, Fall 1983
- **Summer Issue,**
1983, Vol. 26:2—CO_2, mussel watch, warm-core rings, MIZEX, the U.S. EEZ.
- **Summer Issue,**
1982, Vol. 25:2—Coastal resource management, acoustic tomography, aquaculture, radioactive waste.
- **Summer Issue,**
1981, Vol. 24:2—Aquatic plants, seabirds, oil and gas, oceanography and archaeology, and more.
- **Ocean Energy,**
Vol 22:4, Winter 1979/80.
- **Ocean/Continent Boundaries,**
Vol 22:3, Fall 1979.
- **The Deep Sea,**
Vol 21:1, Winter 1978.
- **Summer Issue,**
1977, Vol. 20:3—The 200-mile limit, the Galápagos rift discovery, nitrogen fixation, shark senses.
- **Sound in the Sea,**
Vol. 20:2, Spring 1977.

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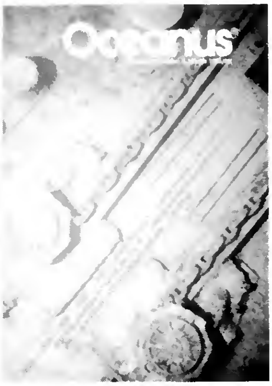

The Titanic: Lost and Found

Vol. 28:4, Winter 1985/86—The most comprehensive account available of the *Titanic*'s loss in 1912 and recent discovery. Includes a detailed account of how the ship was found, a profile of discoverer Robert Ballard, details of the *Argo* system used to find the ship, as well as articles containing many new historical details of the wreck.

Beaches, Bioluminescence, Pollution, and Reefs

Vol. 28:3, Fall 1985—Articles deal with topics of great current interest, such as latest scientific perspectives on oil pollution, threats to the beaches of the U.S. East Coast, the strangely lit world of the deep ocean, and the unique ecosystems of Australia's Great Barrier Reef.

The Oceans and National Security

Vol. 28:2, Summer 1985—The U.S. Navy's effectiveness relies on proper use of strategy, technology, and marine science. This issue looks at all these areas: from details of specific weapons systems, to the proper role of the U.S. Navy, to the importance of marine science research. Additional articles examine the Soviet Navy and the U.S. Coast Guard.

Marine Archaeology

Vol. 28:1, Spring 1985—Details of a rapidly expanding discipline with strong ties to oceanography. Articles deal with basic principles of marine archaeology, life on the continental shelves during the last ice age, some specific sites, Polynesian navigation, legal aspects, Atlantis and catastrophe theory, and more.

other available issues...

- **The Exclusive Economic Zone,**
  Vol. 27:4, Winter 1984/85—Options for the U.S. EEZ.
- **Deep-Sea Hot Springs and Cold Seeps,**
  Vol. 27:3, Fall 1984—A full report on vent science.
- **El Niño,**
  Vol. 27:2, Summer 1984—An atmospheric phenomenon analyzed.
- **Industry and the Oceans,**
  Vol. 27:1, Spring 1984
- **Oceanography in China,**
  Vol. 26:4, Winter 1983/84
- **Offshore Oil and Gas,**
  Vol. 26:3, Fall 1983
- **Summer Issue,**
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  Vol. 24:1, Spring 1981.
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  Vol. 23:3, Fall 1980.
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- **A Decade of Big Ocean Science,**
  Vol. 23:1, Spring 1980.
- **Ocean Energy,**
  Vol. 22:4, Winter 1979/80.
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