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The Arctic region is remote and is a hostile place to study, work, and live. Because of the environmental extremes, particularly cold temperatures, and the year-round presence of ice in the sea, the entire region has been the realm of the Eskimo, the explorer, the adventurer, and the sportsman and, thus, has only recently been scrutinized by the scientific and engineering commmunities. The presence, and apparently specialized nature, of Soviet submarines in the Arctic has encouraged the U.S. Navy to take a more active role in investigating the Arctic environment especially relevant to antisubmarine warfare. The material presented here is an abridgment of some of the knowledge of the Arctic environment relevant to specific disciplines and is a starting point for new investigators of Arctic phenomena pertinent to naval operations. The value added to the material assembled here is based on the collective polar experience of the authors, mainly in the form of practical evaluation of the sources and the clarification of subtle differences. The references pertaining to specific subjects will provide an excellent starting point for investigators.

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March 1986 NORDA **Report 138**

A Compendium of Arctic Environmental Information

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Foreword

The Arctic region is a remote, hostile place to study, work, and live. Because of the environmental extremes—particularly the cold temperatures—and the year-round presence of ice in the sea, the entire region has been the realm of the Eskimo, the explorer, the adventurer, and the sportsman. This region has only recently been scrutinized by the scientific and engineering communities. The presence of specialized Soviet submarines in the Arctic has encouraged the U.S. Navy to take a more active role in investigating the Arctic environment—investigations that are especially relevant to antisubmarine warfare. The material presented here is an abridgment of some of the knowledge of the Arctic environment relevant to specific disciplines, and is a starting point for new investigators of Arctic phenomena pertinent to naval operations.

R. P. Onorati, Captain, USN
Commanding Officer, NORDA

Executive summary

This material is an abridgment of some of the knowledge of Arctic environmental phenomena pertinent to naval operations. The added value of the material assembled is the collective polar experience of the authors, mainly in the form of practical evaluation of the sources, clarification of subtle differences, and personal field experiences. The references pertaining to specific subjects will provide a review and a starting point for investigators who require more detailed treatment. This compendium will be reviewed and revised as appropriate.

Acknowledgments

The Polar Oceanography Branch of the Naval Ocean Research and Development Activity has received numerous requests for Arctic environmental information. These many requests reflect the increased interest and expansion of the Navy's Arctic programs. This report is a revision of NORDA Technical Note 290 by Dr. J. P. Welsh. Technical Note 290 was a "best seller" in the sense that two printings were required to meet the requests received. To satisfy the requests, information has been assembled and directed toward each specific need. In the process it became apparent that many of the requests were repetitious; thus, a compendium became desirable to minimize the impact on our manpower. Toward this end, this report has been assembled.

The information gathering was accomplished during the conduct of work for many sponsors and during nonsponsored hours (weekends, etc.) of the authors.

Special mention is made of the financial support provided by Mr. C. Stewart, AEAS program (6.3); Dr. R. Martin, NORDA 6.2 Coordinator; Dr. H. Eppert, NORDA Associate Technical Director/Director, Ocean Science Directorate (6.1); and Dr. J. Andrews, NORDA Technical Director, for the preparation of the original version of this report.

This revision was made possible through funding provided by Dr. H. Eppert, NORDA Associate Technical Director and Director, Ocean Science Directorate. The assistance in preparation provided by Ms. Bonnie Head is gratefully acknowledged.

Contents

A compendium of Arctic environmental information

1. Sea ice

Introduction

This section is an overview of sea ice as a material and an environmental phenomenon. A glossary of sea ice terms is provided at the end of this section. Examples from our photographic archive are provided to illustrate some of the World Meteorological Organization (WMO) sea ice nomenclature as Appendix O.

The ice canopy that covers the Arctic Ocean and its marginal seas is a dynamic body that varies in its extent from year to year. During a single year the ice coverage may expand from a summer average minimum of 5.2 million square kilometers to a winter average maximum of 11.7 million square kilometers. Figure 1.1 is an example of an arbitrary division of the Arctic into regions.

The ice coverage usually reaches its minimum extent by late summer. In mid to late September, with the onset of continuous, below-freezing air temperatures, the ice begins to grow seaward from the coastlines, within the openings in the existing ice fields, and outward from the pack ice margin. The southward growth and transgression of drifting sea ice usually continues until March when the ice limits have reached their maximum extent. Then, a slow northward regression begins and continues until early September when the ice, again, reaches its minimum extent. Figure 1.2 illustrates the average annual maximum and minimum ice limits in the Arctic and sub-Arctic regions. The area in Figure 1.2, which lies between the minimum ice extent in the late summer and the maximum ice extent in late winter, has been called the marginal or seasonal sea ice zone.

The sea ice cover, with the exception of shorefast ice and bay ice, is in near-constant motion. The major forces that produce ice motion and deformation are winds and currents. In some areas near the edge of the ice cover, waves and swell also play an important role. Variable stresses (tensile, shear, and compressive) within the ice fields, created by the effects of winds, currents, gravity, and temperature changes, cause ice floes to fracture and separate producing leads (open water lanes) and polynyas (open water, lake like). Differential ice motion along these openings may cause floe collision, which results in the formation of ice hummocks and ridges. Leads can be very narrow or many meters (or even kilometers) wide and may extend over many kilometers in length as navigable lanes of open water. Ice ridges can reach heights of 10 m and may have keels reaching depths as great as 50 m. Pressure ridges are usually formed from the thinner ice types, although ridges can occur in any thickness of sea ice and in all ice types at any season.

Collision of the moving pack ice with the shorefast ice creates a dense, chaotic zone of ice rubble, hummocks, and pressure ridges. This narrow zone, called a flaw, separates the generally smooth shorefast ice from the topographically complex, continually moving pack ice.

During the last decade, the understanding of sea ice behavior has increased substantially. Modeling this behavior has improved because of the advances both in computer hardware and software and in numerical solution techniques for solving complicated problems. The techniques used to model sea ice behavior are some of the most sophisticated in use anywhere today (Pritchard, 1980).

Models are used in a diverse range of applications. These applications include understanding climate dynamics, determining oil spill trajectories, estimating loads that might be applied to a fixed structure operating within the ice cover, estimating noise generated by the ice cover, or warning of possible future ice invasions during petroleum drilling operations in open-water conditions.

Development of sea ice

Several basic stages of ice development are categorized by age and/or thickness. New ice is a general term for recently formed ice that includes frazil ice, grease ice, slush, and shuga. These types of ice are composed of ice crystals that are only weakly frozen together and have a bulk salinity usually greater than 5 parts per thousand (ppt). Later stages of ice development include nilas, which is up to 10 cm thick, and young ice, which is 10–30 cm thick. First-year ice has several subcategories, but in all cases this ice type has, by definition, formed in one growth season. It can range from 30 cm to 2 m in thickness, has

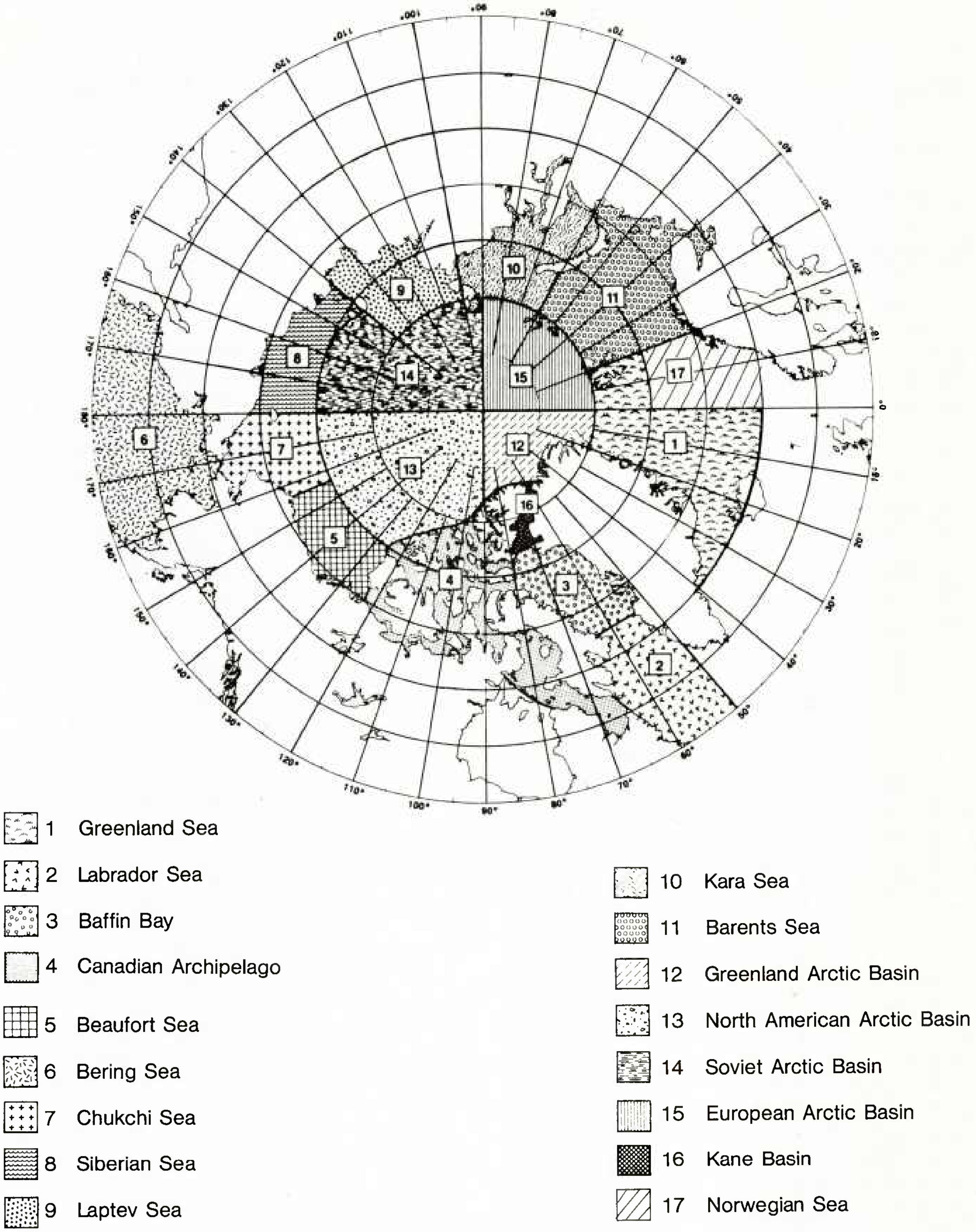


Figure 1.1. Arctic geographic divisions.

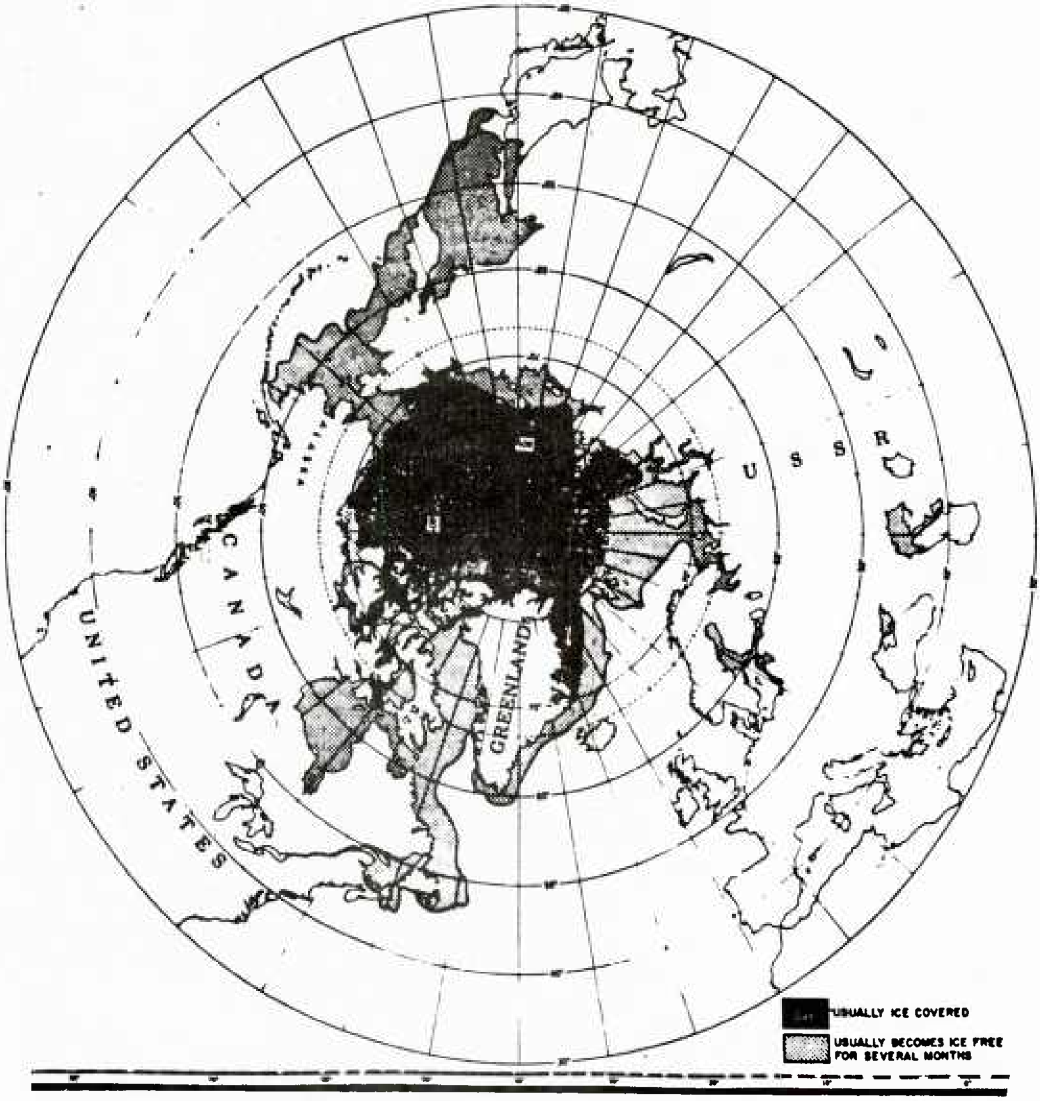


Figure 1.2. Mean maximum and mean minimum limits of sea ice in the Northern Hemisphere.

a relatively smooth surface (if undeformed), and a salinity between 5 and 10 ppt. The term, old ice, includes both second-year ice (ice that has passed through one melt season) and multiyear ice (ice that has passed through two or more melt seasons). These ice types generally have a salinity less than 1 ppt in the upper several centimeters. They are characterized by an irregular, undulating topography and heterogeneous bulk properties that result mainly from the summer erosional processes of melting and water runoff. Multiyear ice thicknesses may average from 3 to 4 m at the end of the winter growth period. For more information about sea ice terminology, including pictures, the reader should consult the WMO report on Sea Ice Nomenclature (WMO, 1970, out of print). The more common terms are described in the glossary of this section. Photographic examples from our archives are included as Appendix O.

Ice islands

Large, tabular sections of land ice (up to 60 m thick and 30 km wide), called ice islands, occasionally break away from the northern edge of the Ellesmere Island ice shelf to join the moving pack ice. These ice islands float slowly in an erratic, large, clockwise circle around the North

American side of the Arctic Ocean (Beaufort or Pacific Gyre) and eventually disintegrate or exit into the Greenland Sea (via the East Greenland Drift). Some have survived or have been recognizable for as long as three decades.

Icebergs

Icebergs, which are much smaller than ice islands, break off the seaward ends of glaciers in Greenland, Northeastern Canada, Svalbard, and the Soviet Arctic. But, the primary source of icebergs is the Greenland ice sheet, which has a maximum thickness of 3300 m, and annually calves about 240 km^3 of ice into the surrounding seas. Because of the geographically limited distribution of iceberg sources, icebergs are not a serious problem in the North Pacific, the Bering Sea, or any part of the central Arctic Ocean.

Estimates of icebergs spawned annually by the Greenland ice sheet vary from 20,000 to 34,000 with most being produced by west coast Greenland glaciers. Although these statistics are numerically impressive, they do not provide the volumetric or mass information needed for estimating the noise effects on naval operations or threats to navigation. The iceberg drift pattern is such that icebergs formed along the east coast usually drift around the southern tip of Greenland and then move north, joining the drift of the icebergs produced by the large outlet glaciers located along the west coast. This northern drift continues up to Baffin Bay, where the icebergs swing around and start moving south along the coasts of Baffin Island, Labrador, and Newfoundland. They finally reach the Grand Banks and ultimately melt in the North Atlantic. Icebergs make or are the sources of distinctive noise in the Arctic, especially in the potential choke point areas of the eastern Arctic.

Salts/impurities in sea ice

Naturally occurring sea ice contains either dissolved or precipitated salts (in brine pockets in the ice). Figure 1.3 shows the complex phase diagram of ''standard'' sea ice, which is based on the formula of standard sea water. The solid phase of the ice is essentially pure H_2O. Substitutional impurities in the lattice are rare; thus, the impurities occur between ice crystals and in the brine pockets.

Growth of sea ice

The condition necessary for the growth of sea ice from the surface of sea water is that the water temperature be below the freezing point, which is about $-2^{\circ}C$ (Fig. 1.3). Air temperatures in the Arctic are typically well below $-2^{\circ}C$ and adequately promote sea ice growth. Because of the natural movement of the sea surface, early stages of sea ice growth are not easily described. In very early stages small (millimeter-sized), individual ice discs grow with the (principal hexagonal) C-axis vertical, since growth perpendicular to this axis is most rapid. Water motion tilts the discs, keeps them reasonably rounded by collisions with nearby crystals, and promotes their fusion with other crystals by bringing them into contact under pressure. The newly forming ice cover is thus made up of chaotically oriented ice crystals.

As the initial layer solidifies, further growth on the bottom surface is concentrated at those crystals with C-axis horizontal (growth in the vertical direction is then favored), and this orientation is thus predominant for the remainder of the growth of the ice. The ice is now a few centimeters thick. Changes occur with time, such as gravity separation of brine and temperature separation of phases for individual salts (Fig. 1.3). The result is a stratified, both vertically and horizontally, mass of sea ice consisting of ice, salts, and air. Ice crystals growing at the base of an ice sheet often show preferred orientation related to local water flow (current).

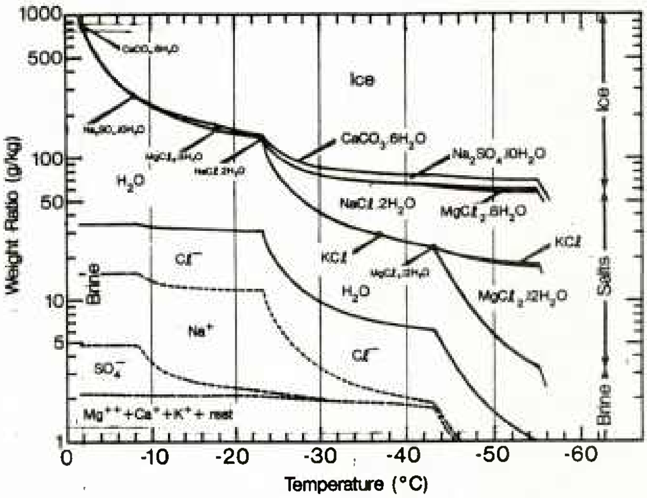


Figure 1.3. Phase relations for ''standard'' sea ice (Assur, 1958).

Characterization of sea ice

Table 1.1 shows the potential capability for observations and measurements in the Arctic environment. Individual entries are subject to interpretation. Table 1.2 provides some examples of Sea Ice Characteristics and Arctic environmental properties and the equipment used to measure them. The characterization of sea ice and the associated environment may require some, all, or more than those methods shown in Table 1.2.

Table 1.1. Some Arctic environmental parameters versus observational platforms and measurement capabilities.

Platforms	Satellite						Airborne												Ships/Icebreakes/Ice Stations																Buoys			Submarines					Models	
Sensors Models Environmental Parameters	Visual	Infrared	Passive Microwave	Synthetic Aperture Radar	Radar Scatterometer	Radar Altimeter	Visual	Infrared	Laser	Reflectometer	Passive Microwave	Synthetic Aperture Radar	Impulse Radar	Radar Scatterometer	Ice Penetrometer	Magnetometer	Gravimeter	AXBT	CTD	Current Meters	Bottom Cover/Sampler	Seismic	XBT	XSV	Wave Height Meter	Magnetometer	Gravimeter	NAVSAT	Electronic Distance Measurements	Ice Cores/Drilling	Impulse Radar	Trawls/Net	PDR/Calcomp	Fixed Bottom Founded Sonar	Atmosphere Sensors	Ocean Sensors	Navigation	SSXBT	SSXSV	Ice Bottom Sounder	Depth Sounder	Side-Scan Sonar	PIFS-N (120 km resolution)	Regional (50 km resolution)
Atmosphere																																												
Pressure																																			D									
Temperature																																			D									
Winds																																			D									
Precipitation																																												
Sea Ice																																												
Ice Edge	D	D	D	D	D	D	D	D	D	D	D	D		D																													I	I
Geographic Distribution	D	D	D	D			D	D		D	D																																I	I
Motion/Deformation	D	D	D	D			D	D			D	D																	D	D					D			D						I	I
Concentration	D	D	D	D			D	D			D	D																														D	I	I
Thickness	I	I	I	I			I	I	I		I			I	D															D	I			D						I			I	I
Ridges														I																														
Distribution				D			D	D	D		I	D	D	I																										D		D	I	I
Height							I		D				D																															
Depth/Keel							I		I																					D				D						D				
Openings	D	D	D	D			D	D		D	D	D	D	D																				D						D		D		
Ice Properties																																												
Physical																														I														
Chemical																														I														
Mechanical																														I														
EM																														I														
Sound Speed																														I														
Optical																														I						D								
Ocean																																												
Wave Height				I	I	I	I	I	D		I	I		I											D											D								
Sea Surface Temperature		D	D					D			D								D				D													D								
Temperature Profiles																		D	D				D	I												D		D	I					
Salinity Profiles																		I	D					I												I			I					
Density																		I	I				I	I												I		I	I					
Currents	I																			D																D								
Internal Waves																		I	I				I													I		I						
Optical Properties																														I						D								
Biological																																D												
Depth									D												D												D			D					D			
Sound Speed Profiles																		I	I				I	D												I		I	D					
Bottom																																												
Topography									D																								D									D		
Composition																					D	I																						
Subbottom Stratagraph																	I				D	D				I	I																	
Geophysical																																												
Magnetics																D										D																		
Gravity																	D										D																	

D—Direct
I—Indirect or inferred

The most prominent feature of the characterization of environmental properties in the Arctic is variation. Figure 1.4 is an example of the variation of salinity in a cross section of multiyear ice. Note that variability exists in both horizontal and vertical directions.

Figure 1.5 shows examples of the variation in ice density, temperature, and salinity, as well as the derived parameter of brine volume going from the ice surface (air/ice) to the ice/water boundary. Table 1.3 summarizes ice property measurements used for evaluating the performance of the

Table 1.2. Some sea ice characteristics and equipment used to measure them.

Measurement	Equipment
snow thickness	meter stick
snow density	snow tubes, triple beam balance
snow temperature	thermistor and bridge
ice thickness	hand auger, electric drill with auger, tape with toggle
ice density	calipers, meter stick and triple beam balance (also considering a diesel or glass bead displacement technique)
ice salinity	core section, salinometer
radiation	portable microwave radiometer with active source
ice temperature	thermistor and bridge
ice camp position	satnav
ice floe movement	mini-ranger
presure ridge height, slope, width	level, tape
ice block size distribution	tape
temperature distribution in a refreezing lead	thermistor array, recorder
air temperature, wind speed and direction, relative humidity, solar duration, barometric pressure	automatic weather station
cloud type and cover	observer
radiation from refreezing lead	microwave radiometer
pressure ridge keel depth and profile	sonar

U.S. Coast Guard icebreaker POLAR STAR. The reason for showing Figures 1.4 and 1.5 and Table 1.3 is to focus on the variation in these environmental properties. The inferred strength values have been arranged into histograms in Figure 1.6. This further emphasizes and demonstrates the variability, especially the lack of central tendency, thus encouraging caution for using the arithmetic mean or root mean square as descriptive statistics for ice properties.

Figure 1.7 provides one additional example to encourage attention to the necessity of examining the underlying distribution of an Arctic environmental property. The histogram of terrain height (an estimator of ice roughness for the top surface) is clearly asymmetrical; thus, the first two moments are insufficient descriptive statistics.

Other properties of sea ice

The following summarizes some of the values used to describe the range for mechanical, thermal, and electrical properties of sea ice. Three references are recommended for more detailed summaries: Weeks and Ackley (1982), Schwartz and Weeks (1977), and Mellor (1983).

Mechanical properties

Arctic sea ice is a mixture of undeformed and deformed masses of polycrystalline ice that consists of ice crystals in various crystallographic orientations. Various impurities (salts) are distributed throughout the volume being separated by gravity in concert with phase changes with temperature and pressure. These changes include air and occasionally sediment, rocks, and biological incorporations that are alive, growing, or dead; therefore, the variability for any one property can be considerable. The dynamics of a material, such as sea ice, very near phase transition boundaries can be dramatic. Defining the scale in time and space of the properties of interest is critical. For example, at a geographic scale of kilometers the rheological behavior of sea ice may be described as viscoelastic, whereas the behavior at the scale of 1 m (accounting for loading rate) may be plastic. The transition from the elastic region (Hooke's law applies) through the elastic limit and into the plastic region is not linear for sea ice. The number of sets of elastic parameters possible for sea ice is dependent on distribution of crystal size and orientation related to the direction in which freezing has occurred. Definitive experimental data to determine the number of sets for polycrystalline anisotropic sea ice is not available. The viscous behavior of sea ice is difficult to describe because of the inhomogeneous application of the stress (hard to measure in real-life field experiments) and rate of application. Inference from glacier ice studies have been used to gain some insight. In general, studies of the rheological behavior of sea ice in the environment, at all scales and strain rates, are extremely rare.

Ice strength

Measurements of flexural strength (in situ) of sea ice have been conducted by independent investigators and, more recently, by interested oil companies. Figure 1.8 gives an example of an eyeball fit curve (Welsh, 1978) that shows a relationship between the flexural strength of sea ice and the square root of the brine volume (derived from temperature and salinity measurements of the ice obtained in a core). This curve was used to infer flexural strength for evaluating the performance of the POLAR STAR during trials in Antarctic sea ice. Note that the range of values

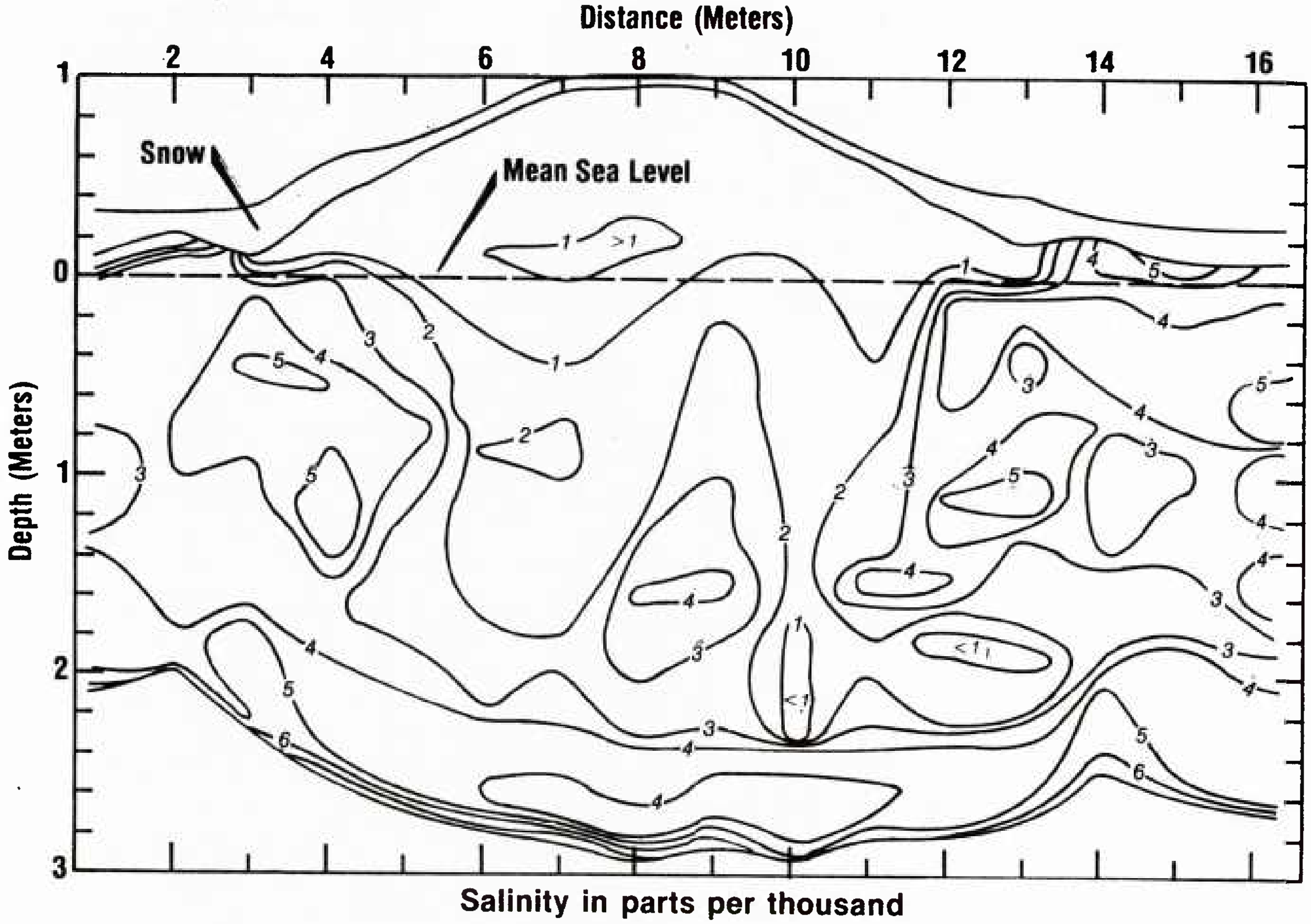


Figure 1.4. Cross section of multiyear ice illustrating the variability of salinity distribution (Cox and Weeks, 1975).

is small for inferred flexural strength. Figures 1.9 and 1.10 are provided for compressive and shear strength, respectively. Note that the range is greater for both compressive and shear than for flexural.

The least ambiguous in situ testing has been for flexural strength, whereas the sample preparation for compressive and shear tests has apparently affected the outcome. Thus, the measured values have been less than satisfying.

Thermal properties of sea ice

The latent heat of sea ice fusion is actually a combination of that for pure ice (no salts), approximately 80 cal/gram (at 0°C) and the sum of the salts (impurities) present. The latent heat of vaporization for pure ice (no salts) is 597 cal/gram (at 0°C). Sublimation (ice at 0°C to water vapor at 0°C) requires approximately 677 cal/gram and is not an uncommon process in the Arctic. Because of the complexity of sea ice and the continuous phase change from sea ice to sea water, there is no true latent heat of melting for sea ice.

The specific heat of sea ice varies with temperature and salinity from 0.5 cal/g/°C at −2°C to 0.46 cal/g/°C at −22°C for salinity of 0 ppt and 11.3 cal/g/°C for −2°C to 0.55 cal/g/°C at −22°C for salinity of 10 ppt.

The thermal conductivity for sea ice has been modeled by a number of individuals. In general, because the conductivity of the brine (salts) is lower than pure ice (H_2O) the value of the thermal conductivity of sea ice will always be smaller than for pure ice. The models vary in their treatment of the distribution and orientation of the conductors (brine) for sea ice and air (bubbles). The variation with changes in temperature and salinity can be greater than a factor of two with an apparently asymptotic approach to the value of pure ice at temperatures of −15°C to −20°C.

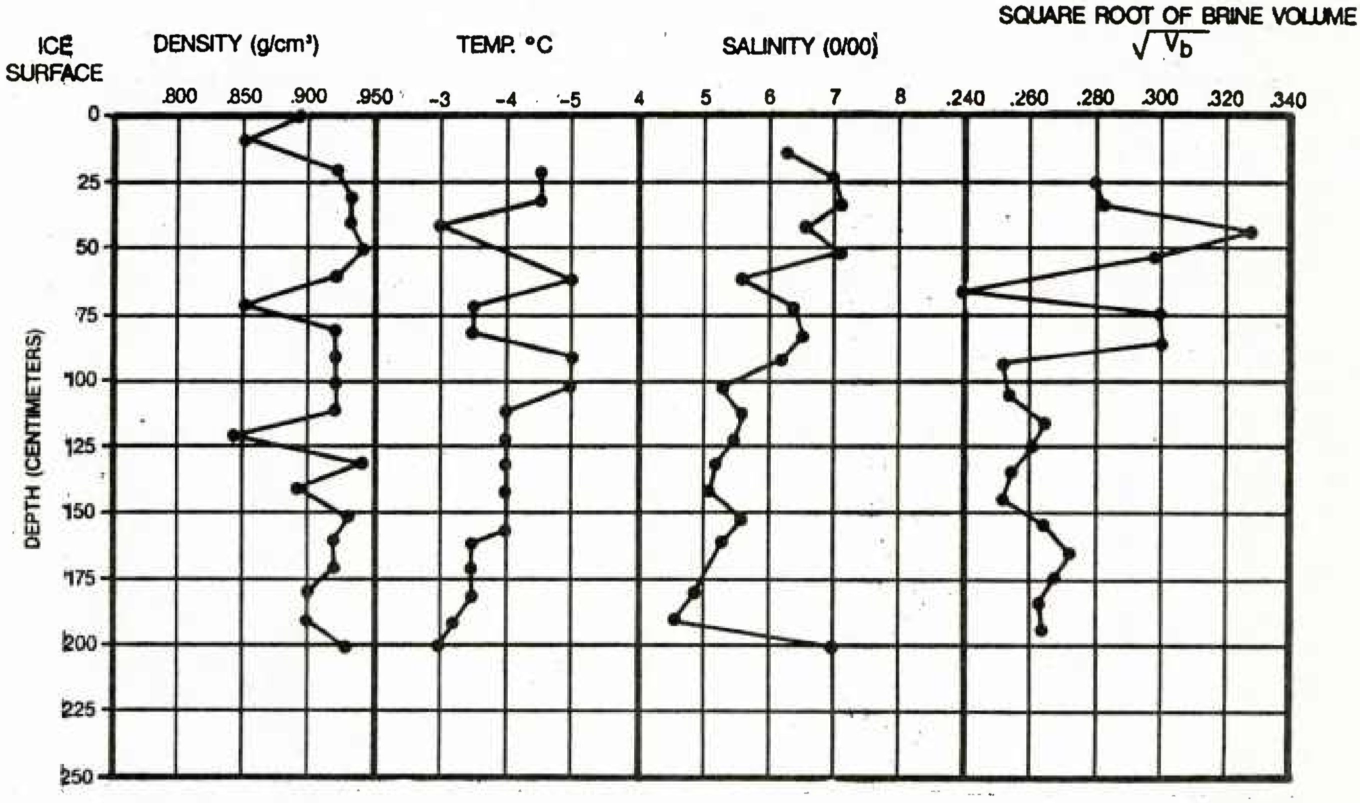


Figure 1.5. Density, temperature, salinity, and brine volume profiles from ice core taken 23 December 1977 in McMurdo Sound, Antarctica (Welsh, 1978).

Table 1.3. Summary of ice property measurements for pack ice test of 23 December 1977.

Sample Depth (approximate cm)	Temperature (O°C)	Density (g/cm^3)	Salinity (ppt)	V_b	Inferred Strength (kg/cm^2)		
					Flexural	Shear	Compressive
4.9	—	0.89	12.7	—	—	—	—
14.6	—	0.85	6.3	—	—	—	—
24.4	−4.5	0.92	7.0	0.280	2.7	6.2	7.9
34.2	−4.5	0.93	7.1	0.282	2.7	6.2	7.9
43.9	−3.0	0.93	6.6	0.327	2.1	5.2	6.3
53.7	−4.0	0.94	7.1	0.297	2.5	5.7	7.4
63.4	−5.0	0.92	5.6	0.239	3.4	7.4	9.9
73.2	−3.5	0.85	6.4	0.299	2.4	5.6	7.2
83.0	−3.5	0.92	6.5	0.302	2.4	5.6	7.1
92.7	−5.0	0.92	6.2	0.251	3.6	7.0	9.2
102.5	−5.0	0.92	5.3	0.233	3.4	7.6	10.0
112.3	−4.0	0.92	5.6	0.264	2.9	6.5	8.5
122.0	−4.0	0.84	5.5	0.261	2.9	6.6	8.6
131.8	−4.0	0.94	5.2	0.254	3.1	6.8	9.0
141.5	−4.0	0.89	5.1	0.251	3.1	7.0	9.2
151.3	−4.0	0.93	5.6	0.264	2.9	6.6	8.5
161.1	−3.5	0.92	5.3	0.272	2.8	6.4	8.2
170.8	−3.5	0.92	5.1	0.267	2.8	6.5	8.4
180.6	−3.5	0.90	4.9	0.262	2.9	6.6	8.6
190.4	−3.2	0.90	4.6	0.264	2.9	6.6	8.5
200.1	−3.0	0.93	7.0	0.337	2.0	5.1	6.0

Date: 12/23/77 Time: 1810 Location: 73°27′S Latitude; 171°10′E Longitude Air Temperature: −2.2°C
Wind: Variable 3 knots Weather: Snowing Thickness (m): Ice—2.05; Snow—0.28; Freeboard—0.13
Comments: Color is gray-blue to dark gray top to bottom; bleeding in lower 0.5 m; fine grain, small crystal size; very little stratification apparent; no bubbles.

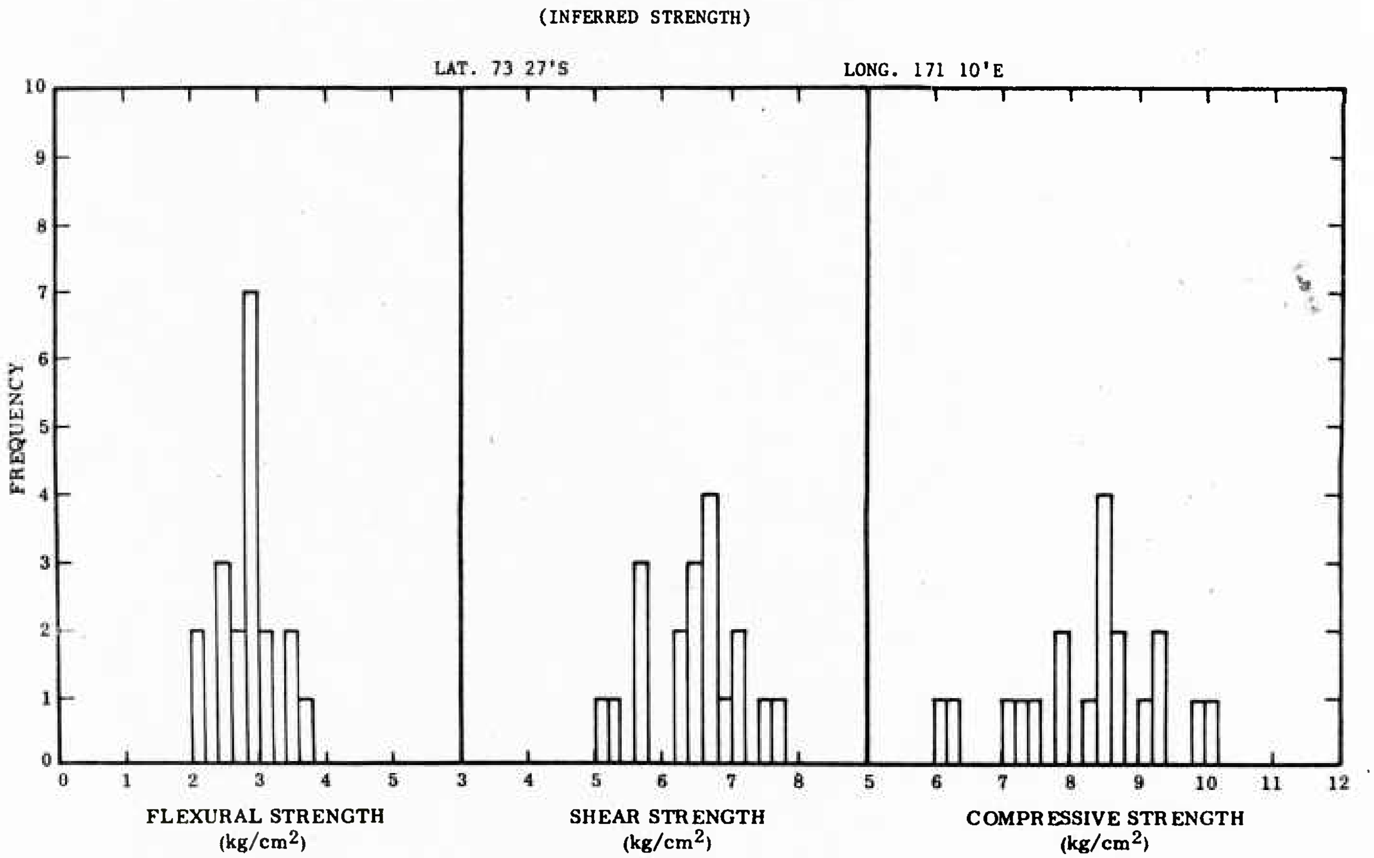


Figure 1.6. *Histograms of inferred flexural, shear, and compressive strength, 23 December 1977.*

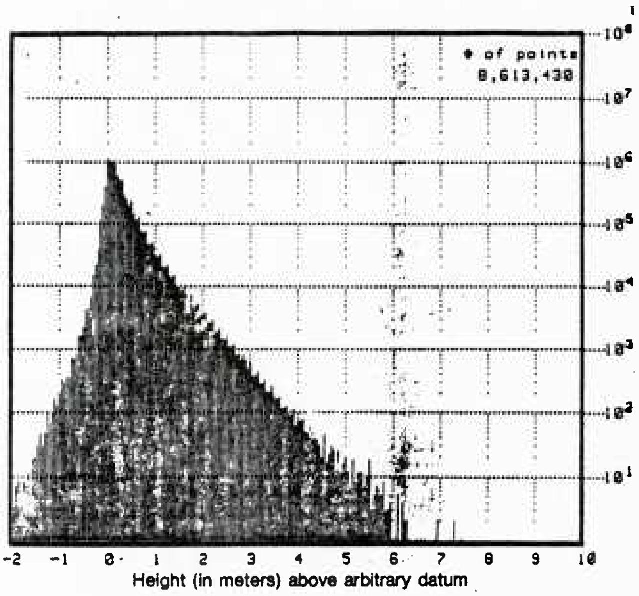


Figure 1.7. *Histogram of sea ice terrain height.*

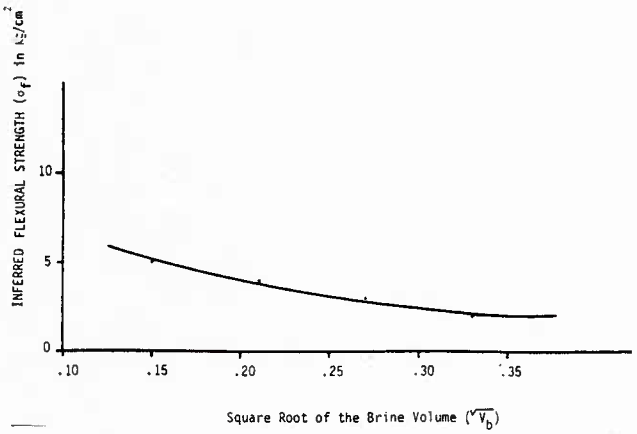


Figure 1.8. *Inferred flexural strength versus square root of the brine volume (after data in Weeks and Assur, 1967).*

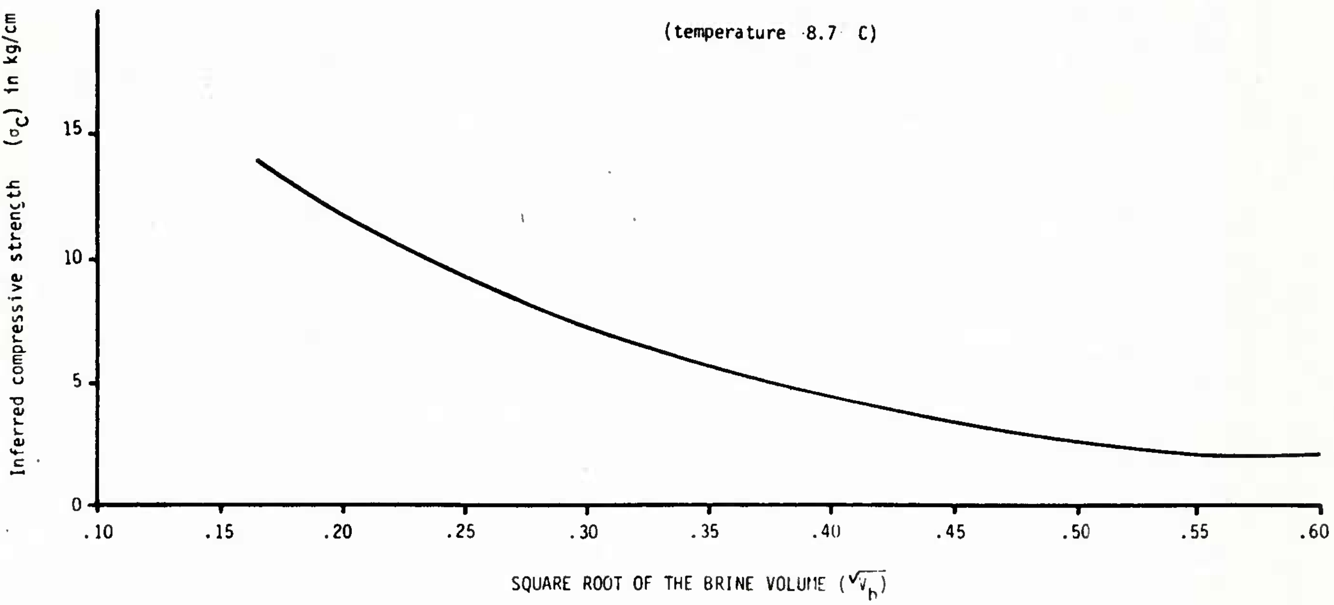


Figure 1.9. Inferred compressive strength (after data from Peyton in Weeks and Assur, 1967).

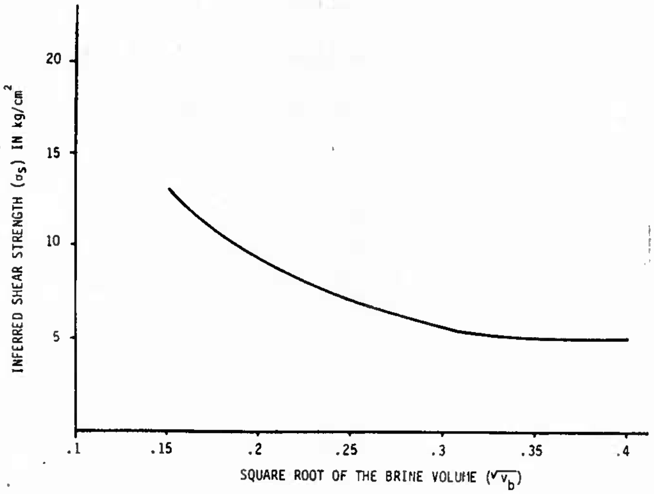


Figure 1.10. Inferred shear strength (after data from Paige and Lee in Weeks and Assur, 1967).

Electrical properties of sea ice

The brine cells, often cylindrical in shape, act like low resistance filaments and appear to dominate the electrical behavior of sea ice. It has been demonstrated that the electrical conductivity and the dielectric constant are anisotropic with respect to the orientation of the C-axis of the ice crystals and that the variation is very large. Resistance measurements are rare and range from 10^2 to 10^4 ohmmeters for a horizontal direction to 10^2 ohmmeters for the vertical direction in sea ice.

Measurements of capacitance and resistance in a frequency range of 20 Hz to 5 MHz showed dielectric constants of 10^5 to 10^6 at the lowest frequencies.

Bibliography

Assur, A. (1958). Comparison of a Sea Ice and Tensile Strength. In *Arctic Sea Ice*, National Acad. of Sci., National Research Council Pub. 598.

Central Intelligence Agency (1978). *Polar Regions Atlas*, May.

Cox, G. F. N. and W. F. Weeks (1975). *Brine Drainage and the Initial Salt Entrapment in Sodium Chloride Ice.* CRREL Rep., Hanover, NW Hampshire, Rep. 345.

Ice Engineering (1982). Engineer Manual No. 1110-2-1612. Department of the Army, U. S. Army Corps of Engineers, Washington, D.C. 20314.

LaChapelle, E. R. (1969). *Field Guide to Snow Crystals.* University of Washington Press, Seattle, Washington.

Mellor, M. (1983). *Mechanical Behavior of Sea Ice.* CRREL monograph 83-1, June.

Pritchard, Robert S. (1980). Sea Ice Processes and Models. *Proceedings, Arctic Ice Dynamics Joint Experiment, International Commission on Snow and Ice Symposium*, University of Washington Press, Seattle, Washington.

Schwartz, J. and W. F. Weeks (1977). Engineering Properties of Sea Ice. *J. Glaciology*, v. 19, n. 81, pp. 499–531.

U.S. Naval Oceanographic Office (1958). *Oceanographic Atlas of the Polar Seas, Part II: Arctic.* H. O. Publ. No. 705, NSTL, Mississippi.

Weeks, W. F. and S. F. Ackley (1982). *The Growth, Structure, and Properties of Sea Ice*. CRREL monograph 82-1, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755.

Weeks, W. F. and A. Assur (1967). Mechanical Properties of Sea Ice. In *Cold Regions Science and Engineering, Part II, Physical Science, Sect. C—Physics and Mechanics of Sea Ice*. CRREL, Hanover, New Hampshire.

Weeks, W. F. and M. Mellor (1984). Mechanical Properties of Ice in the Arctic Seas. *Proceedings, Arctic Policy and Technology*, Ira Dyer and Chryssostomos Chryssostomidis (eds.), Hemisphere Publishing Corp., pp. 235–259.

Welsh, J. P. (1978). *Test and Evaluation of the CGC Polar Star*, WAGB10, Vols. I, II, III, and IV. Naval Ocean Research and Development Activity, NSTL, Mississippi, NORDA Report 22.

Welsh, J. P. and J. Reshew (1985). *Proceedings, Arctic Oceanography Conference and Workshop*. Sponsored by the Naval Ocean Research and Development Activity and Commander, Naval Oceanography Command, NSTL, Mississippi, 11–14 June.

World Meteorological Organization (1970). *WMO Sea-Ice Nomenclature*. WMO/OMM/BMO-No. 259, TP. 145, Geneva, Switzerland.

Glossary of Ice Terms (Source: WMO Sea Ice Nomenclature).

aged ridge—ridge that has undergone considerable weathering, etc. These ridges are best described as undulations.

annual ice—see "first year ice."

bare ice—ice without snow cover.

belt—a large feature of pack ice arrangement, longer than it is wide, from 1 km to more than 100 km in width.

bergy bit—a large piece of floating glacier ice, generally showing less than 5 m above sea-level but more than 1 m, and normally about 100–300 m^2 in area.

beset—situation of a vessel surrounded by ice and unable to move.

big floe—see floe.

bight—an extensive crescent-shaped indentation in the ice edge, formed by either wind or current.

brash ice—accumulations of floating ice made up of fragments not more than 2 m across, the wreckage of other forms of ice.

bummock—from the point of view of the submariner, a downward projection from the underside of the ice canopy; the counterpart of a hummock.

calving—the breaking away of a mass of ice from an ice wall, ice front, or iceberg.

close pack ice—pack ice in which the concentration is 7/10 to 8/10 (6/8 to less than 7/8), composed of floes mostly in contact.

compacted ice edge—close, clear-cut ice edge compacted by wind or current; usually on the windward side of an area of pack ice.

compacting—pieces of floating ice are said to be compacting when they are subjected to a converging motion, which increases ice concentration and/or produces stresses that may result in ice deformation.

compact pack ice—pack ice in which the concentration is 10/10 (8/8) and no water is visible.

concentration—ratio in eighths or tenths of the sea surface covered by ice to the total area of sea surface.

concentration boundary—a line approximating the transition between two areas of pack ice with distinctly different concentrations.

consolidated pack ice—pack ice in which the concentration is 10/10 (8/8) and the floes are frozen together.

consolidated ridge—a ridge in which the base has frozen together.

crack—any fracture that has not parted.

dark nilas—nilas that is under 5 cm in thickness and is very dark in color.

deformed ice—a general term for ice that has been squeezed together and in places forced upward (and downward). Subdivisions are rafted ice, ridged ice, and hummocked ice.

difficult area—a general qualitative expression to indicate, in a relative manner, that the severity of ice conditions prevailing in an area is such that navigation in it is difficult.

diffuse ice edge—poorly defined ice edge limiting an area of dispersed ice; usually on the leeward side of an area of pack ice.

diverging—ice fields or floes in an area are subjected to diverging or dispersive motion, thus reducing ice concentration and/or relieving stresses in the ice.

dried ice—sea ice from the surface of which melt-water has disappeared after cracks and thaw holes have formed. During the period of drying, the surface whitens.

easy area—a general qualitative expression to indicate, in a relative manner, that ice conditions prevailing in an area are such that navigation in it is not difficult.

fast ice—sea ice that forms and remains attached to the coast.

fast ice boundary—the ice boundary at any given time between fast ice and pack ice.

fast ice edge—the demarcation at any given time between fast ice and open water.

finger-rafted ice—type of rafted ice in which floes thrust "fingers" alternately over and under the other.

finger rafting—type of rafting whereby interlocking thrusts are formed, each floe thrusting "fingers" alternately over and under the other. Common in nilas.

firn—old snow which has recrystallized into a dense material. Unlike snow, the particles are to some extent joined together, but unlike ice, the air spaces in it still connect with each other.

first year ice—sea ice of not more than one winter's growth; thickness varies from 30 cm to 2 m.

flaw—a narrow separation zone between pack ice and fast ice, where the pieces of ice are in chaotic state; it forms when pack ice shears under the effect of a strong wind or current along the fast ice boundary.

flaw lead—a passageway between pack ice and fast ice that is navigable by surface vessels.

flaw polynya—a polynya between pack ice and fast ice.

floating ice—any form of ice found floating in water. The principal kinds of floating ice are lake ice, river ice, and sea ice, which form when water freezes at the surface, and glacier ice (ice of land origin), which is formed on land or in an ice shelf. The concept includes ice that is strained or grounded.

floe—any relatively flat piece of sea ice 20 m or more across. Floes are subdivided according to horizontal extent, as follows: giant—over 10 km across; vast—2–10 km across; big—500–2000 m across; medium—100–500 m across; small—20–100 m across.

floeberg—a massive piece of sea ice composed of a hummock or a group of hummocks frozen together and separated from any ice surroundings. It may float up to 5 m above sea level.

flooded ice—sea ice that has been flooded by melt water or river water and is heavily loaded by water and wet snow.

fracture—any break or rupture through very close pack ice, compact pack ice, consolidated pack ice, fast ice, or a single floe resulting from deformation processes. Fractures may contain brash ice and/or be covered with nilas and/or young ice. Length may vary from a few meters to many kilometers.

fracture zone—an area that has a great number of fractures.

fracturing—pressure process whereby ice is permanently deformed and rupture occurs. Most commonly used to describe breaking across very close pack ice, compact pack ice, and consolidated pack ice.

frazil ice—fine spicules or plates of ice suspended in water.

friendly ice—from the point of view of the submariner, an ice canopy containing many large skylights or other features that permit a submarine to surface. There must be more than 10 such features per 30 nautical miles (56 km) along the submarine's track.

frost smoke—fog-like clouds due to contact of cold air with relatively warm water, which can appear over openings in the ice or leeward of the ice edge, and which may persist while ice is forming.

giant floe—see floe.

glacier—a mass of snow and ice continuously moving from higher to lower ground or, if afloat, continuously spreading. The principal forms of glacier are inland ice sheets, ice shelves, ice streams, ice caps, ice piedmonts, cirque glaciers, and various types of mountain (valley) glaciers.

glacier berg—an irregularly shaped iceberg.

glacier ice—ice in or originating from a glacier, whether on land or floating on the sea as icebergs, bergy bits, or growlers.

glacier tongue—projecting seaward extension of a glacier, usually afloat. In the Antarctic, glacier tongues may extend over many tens of kilometers.

gray ice—young ice 10–15 cm thick. Less elastic than nilas and breaks on swell. Usually rafts under pressure.

gray-white ice—young ice 15–30 cm thick. Under pressure more likely to ridge than to raft.

grease ice—a later stage of freezing than frazil ice when the crystals have coagulated to form a soupy layer on the surface. Grease ice reflects little light, giving the sea a matte appearance.

grounded hummock—hummocked grounded ice formation. There are single grounded hummocks and lines (or chains) of grounded hummocks.

grounded ice—ice aground in shoal water.

growler—smaller piece of ice than a bergy bit or floeberg, often transparent but appearing green or almost black in color, extending less than 1 m above the sea surface and normally occupying an area of about 20 m^2.

hostile ice—from the submariner's point of view, an ice canopy that contains no large skylights or other features that permit a submarine to surface.

hummock—a hillock of broken ice that has been forced upward by pressure. May be fresh or weathered. The submerged volume of broken ice under the hummock, forced downward by pressure, is termed a bummock.

hummocked ice—sea ice piled haphazardly one piece over another to form an uneven surface.

hummocking—the pressure process by which sea ice is forced into hummocks. When the floes rotate in the process, it is termed screwing.

iceberg—a large mass of ice usually more than 5 m above sea level, floating or aground, that has calved from a glacier, i.e., fresh-water ice.

iceberg tongue—a major accumulation of icebergs projecting from the coast, held in place by grounding and joined together by fast ice.

ice blink—a whitish glare on low clouds above an accumulation of distant ice.

ice-bound—a harbor, inlet, etc., is said to be ice-bound when ship's navigation is prevented by ice, except possibly with the assistance of an icebreaker.

ice boundary—the demarcation at any given time between fast ice and pack ice or between areas of pack ice of different concentrations.

ice breccia—ice pieces of different age frozen together.

ice cake—any relatively flat piece of sea ice less than 20 m across.

ice canopy—pack ice from the point of view of the submariner.

ice cover—the ratio of an area of ice of any concentration to the total area of sea surface within some large geographic locale; this locale may be global, hemispheric, or prescribed by a specific oceanographic entity such as Baffin Bay or the Barents Sea.

ice edge—the demarcation at any given time between the open sea and sea ice of any kind, whether fast or drifting. It may be termed compacted or diffuse.

ice field—area of pack ice consisting of any size of floes, which is greater than 10 km across.

icefoot—a narrow fringe of ice attached to the coast, unmoved by tides, and remaining after the fast ice has moved away.

ice-free—no sea ice present. There may be some ice of land origin.

ice front—the vertical cliff forming the seaward face of an ice shelf or other floating glacier varying in height from 2 to 50 m or more above sea level.

ice island—Arctic shelf ice floating or aground, extending about 5 m above sea level, thickness varies from 30 to 50 m with an area from thousands of square meters to 500 km^2 or more.

ice jam—an accumulation of broken river ice or sea ice caught in a narrow channel.

ice keel—from the submariner's point of view, a downward-projecting ridge on the underside of the ice canopy; the counterpart of a ridge. Ice keels may extend as much as 50 m below sea level.

ice limit—climatological term referring to the extreme minimum or extreme maximum extent of the ice edge in any given month or period based on observations over a number of years. Term should be preceded by minimum or maximum.

ice massif—a concentration of sea ice covering hundreds of square kilometers, which is found in the same region every summer.

Glossary of Ice Terms (Source: WMO Sea Ice Nomenclature) Cont'd.

ice of land origin—ice formed on land or in an ice shelf, found floating in water. The concept includes ice that is stranded or grounded.

ice patch—an area of pack ice less than 10 km across.

ice port—an embayment in an ice front, often of a temporary nature, where ships can moor alongside and unload directly onto the ice shelf.

ice rind—a brittle, shiny crust of ice formed on a quiet surface by direct freezing or from grease ice, usually in water of low salinity. Thickness to about 5 cm. Easily broken by wind or swell, commonly breaking in rectangular pieces.

ice shelf—a floating ice sheet of considerable thickness that shows 2–50 m or more above sea level and is attached to the coast. Usually of great horizontal extent and with a level or gently undulating surface. Nourished by annual snow accumulation and often by the seaward extension of land glaciers, as well. Limited areas may be aground. Seaward edge is termed an ice front.

ice stream—part of an inland ice sheet in which the ice flows more rapidly and not necessarily in the same direction as the surrounding ice. The margins are sometimes clearly marked by a change in direction of the surface slope but may be indistinct.

ice under pressure—ice in which deformation processes are actively occurring and are a potential impediment or danger to shipping.

ice wall—an ice cliff that forms the seaward margin of a glacier that is not afloat. An ice wall is aground, the rock basement being at or below sea level.

lake ice—ice formed on a lake, regardless of observed location.

large fracture—more than 500 m wide.

large ice field—an ice field over 20 km across.

lead—any fracture or passageway through sea ice that that is navigable by surface vessels.

level ice—sea ice that is unaffected by deformation.

light nilas—nilas that is more than 5 cm in thickness and rather lighter in color than dark nilas.

mean ice edge—average position of the ice edge in any given month or period based on observations over a number of years. Other terms that may be used are mean maximum ice edge and mean minimum ice edge.

medium first-year ice—first year ice 70–120 cm thick.

medium floe—see floe.

medium fracture—from 200 to 500 m wide.

medium ice field—an ice field 15–20 km across.

multiyear ice—sea ice from 2 to 3 m or more thick that has survived at least two summers' melt.

new ice—a general term for recently formed ice that includes frazil ice, slush, and shuga. These types of ice are composed of ice crystals that are only weakly frozen together (if at all) and have a definite form only while they are afloat.

new ridge—ridge newly formed with sharp peaks and slope of sides usually 40°. Fragments are visible from the air at low altitude.

nilas—a thin elastic crust of ice, easily bending on waves and swell and under pressure, thrusting in a pattern of interlocking "fingers" (finger rafting). Has a matte surface and is up to 10 cm in thickness. May be subdivided into dark nilas and light nilas.

nip—ice is said to nip when it forcibly presses against a ship. A vessel so caught, though undamaged, is said to have been nipped.

old ice—sea ice that has survived at least one summer's melt. Most topographic features are smoother than on first-year ice. May be subdivided into second-year ice and multiyear ice.

open pack ice—pack ice in which the ice concentration is 4/10 to 6/10 (3/8 to less than 6/8), with many leads and polynyas, and the floes are generally not in contact with one another.

open water—a large sea of freely navigable water in which sea ice is present in concentrations less than 1/10 (1/8). When there is no sea ice present, the area should be termed ice-free, even though icebergs are present.

pack ice—any area of sea ice, other than fast ice (icebergs and ice islands are not sea ice) no matter what form it takes or how it is disposed.

pancake ice—predominantly circular pieces of ice from 30 cm to 3 m in diameter, and up to about 10 cm in thickness, with raised rims due to the pieces striking against one another. It may be formed on a slight swell from grease ice, shuga, or slush or as a result of the breaking of ice rind, nilas or, under severe conditions of swell or waves, of gray ice. It also sometimes forms at some depth, at an interface between water bodies of different physical characteristics, from where it floats to the surface; its appearance may rapidly cover wide areas of water.

plate ice—same as level ice (level ice preferred).

polynya—any nonlinear-shaped opening enclosed in ice. Polynyas may contain brash ice and/or be covered with new ice, nilas, or young ice; submariners refer to these as skylights. Sometimes the polynya is limited on one side by either the coast (called a shore polynya) or by fast ice (called a flaw polynya). If it recurs in the same position every year, it is called a recurring polynya.

pressure ridge—a line or wall of broken ice caused by compression or shear during collision.

puddle—an accumulation on ice of meltwater, mainly due to melting snow, but in the more advanced stages also to melting ice. Initial stage consists of melted snow patches.

rafted ice—type of deformed ice formed by one piece of ice overriding another.

rafting—pressure processes whereby one piece of ice overrides another. Most common in new and young ice.

ram—an underwater ice projection from an ice wall, ice front, iceberg or floe. Its formation is usually due to a more intensive melting and erosion of the unsubmerged part.

recurring polynya—a polynya that recurs in the same position every year.

Glossary of Ice Terms (Source: WMO Sea Ice Nomenclature) Cont'd.

refrozen lead—a lead that contains ice from wall to wall.

ridge—a line or wall of broken ice forced up by pressure. May be fresh or weathered. The submerged volume of broken ice under a ridge, forced downward by pressure, is termed an ice keel.

ridged ice—ice piled haphazardly one piece over another in the form of ridges or walls. Usually found in first-year ice.

ridged-ice zone—an area in which much ridged ice with similar characteristics has formed.

ridging—the pressure process by which sea ice is forced into ridges.

river ice—ice formed on a river, regardless of observed location.

rotten ice—sea ice that has been honeycombed and is in an advanced state of disintegration.

sastrugi—sharp, irregular ridges formed on a snow surface by wind erosion and deposition. On mobile floating ice the ridges are parallel to the direction of the prevailing wind at the time they were formed.

sea ice—any form of ice originating from the freezing of sea water.

second-year ice—old ice that has survived only one summer's melt. Because it is thicker and less dense than first-year ice, it stands higher out of the water. In contrast to multiyear ice, summer melting produces a regular pattern of numerous small puddles. Bare patches and puddles are usually greenish-blue.

shearing—an area of pack ice is subject to shear when the ice motion varies significantly in the direction normal to the motion, subjecting the ice to rotational forces. These forces may result in phenomena similar to a flaw.

sheet ice—same as level ice (level ice preferred).

shore lead—a lead between pack ice and the shore or between pack ice and an ice front.

shore polynya—a polynya between pack ice and the coast or between pack ice and an ice front.

shuga—an accumulation of spongy white ice lumps, a few centimeters across; they are formed from grease ice or slush and sometimes from anchor ice rising to the surface.

skylight—from the point of view of the submariner, thin places in the ice canopy, usually less than 1 m thick and appearing from below as relatively light, translucent patches in dark surroundings. The undersurface of a skylight is normally flat. Skylights are called large if big enough for a submarine to attempt to surface through them (120 m), or small if not.

slush—snow that is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall.

small floe—see floe.

small fracture—50 to 200 m wide.

small ice cake—an ice cake less than 2 m across.

small ice field—an ice field 10–15 km across.

snow-covered ice—ice covered with snow.

snowdrift—an accumulation of windblown snow deposited in the lee of obstructions or heaped by wind eddies. A crescent-shaped snowdrift, with ends pointing downwind, is known as a snow barchan.

standing floe—a separate floe standing vertically or inclined and enclosed by rather smooth ice.

stranded ice—ice that has been floating and has been deposited on the shore by retreating high water.

strip—long narrow area of pack ice, about 1 km or less in width, usually composed of small fragments detached from the main mass of ice, and run together under the influence of wind, swell, or current.

tabular berg—a flat-topped iceberg. Most tabular bergs form by calving from an ice shelf and show horizontal banding.

thaw holes—vertical holes in sea ice formed when surface puddles melt through to the underlying water.

thick first-year ice—first-year ice over 120 cm thick.

thin first-year ice—first-year ice 30–70 cm thick.

tide crack—crack at the line of junction between an immovable ice foot or ice wall and fast ice, the latter subject to rise and fall of the tide.

tongue—a projection of the ice edge up to several kilometers in length, caused by wind or current.

uniform ice—same as level ice (level ice preferred).

vast floe—see floe.

very close pack ice—pack ice in which the concentration is 9/10 to less than 10/10 (7/8 to less than 8/8).

very open pack ice—pack ice in which the concentration is 1/10 to 3/10 (1/8 to less than 3/8) and water preponderates over ice.

very small fracture—0 to 50 m wide.

very weathered ridge—ridge with tops very rounded, slope of sides usually 20°–30°.

water sky—dark streaks on the underside of low clouds indicating the presence of water features in the vicinity of sea ice.

weathered ridge—ridge with peaks slightly rounded and slope of sides usually 30° to 40°. Individual fragments are not discernible.

weatherings—processes of ablation and accumulation that gradually eliminate irregularities in an ice surface.

white ice—see thin first-year ice.

young coastal ice—the initial stage of fast ice formation consisting of nilas or young ice; its width varyies from a few meters up to 100–200 m from the shoreline.

young ice—ice in the transition stage between nilas and first-year ice, 10–30 cm in thickness. May be subdivided into gray ice and gray-white ice.

2. Arctic oceanography

Introduction

The Arctic Ocean covers approximately 14 million square kilometers. It is one of the least studied of the earth's oceans because of the hostile climate, extensive ice cover, inaccessibility to surface ships, and isolation from population centers. It is also the smallest of the world's oceans. Arctic water is the result of local processes within the basin and its bordering seas. Cooling in winter lowers the water temperature, which results in the formation of a surface ice canopy. The freezing point decreases slightly with increased salt content, the freezing point at 30 ppt = −1.62°C, at 33 ppt = −1.80°C. Sea ice properties depend greatly on its temperature, salinity, and growth history; the salinity of the ice is dependent on the rate of freezing. Slow-freezing retains less salt from the water in which it forms; fast-freezing retains a greater concentration of salt.

When sea water freezes, salt is separated and concentrated between ice crystals and in the water resulting in an increased density of the surface water. This increased density produces convectional mixing that results in an isothermal, isohaline surface layer that may reach 50 m.

The ice cover, under the driving influence of winds and currents, is in continual motion. The resultant stresses produce open water (leads and polynyas), which loses heat to the atmosphere at a rate that may be 2 orders of magnitude greater than through ice (Coachman and Aagaard, 1974). Consequently, the area of open water/thin ice and duration of these features has a profound influence on the Arctic heat budget.

Summer warming can result in the melting of up to 1.5 m of ice. This adds a great deal of fresh water to the surface that can be mixed with underlying sea water through differential movement of ice and through wind-mixing in ice-free areas. These mixing processes maintain a surface salinity greater than 28 ppt. Also, during the summer the rivers discharge fresh water into the surface layer. The water may be warmed by absorption of solar radiation, but where an ice cover exists, the heating effect on the water is slight. In open areas of the bordering seas the surface water may warm to 3°C or more.

The five marginal seas on the Eurasian side of the Arctic occupy 36% of the Arctic Ocean surface area but contain only 2% of its volume of water. With the exception of the Mackenzie River in northern Canada all the major continental rivers reaching the Arctic Ocean flow into these five seas. Therefore, these shallow seas, with a high ratio of exposed surface to total volume and with a substantial input of fresh water in summer, greatly influence surface water conditions in the Arctic Ocean.

In general, the Arctic Ocean is comprised of three water masses:

- The surface layer (Arctic water) has varying characteristics, but it is generally cold (at or near the freezing point); it is relatively dilute, 28–32 ppt at the surface, but below about 50 m the salinity increases sharply with depth. In cold Arctic waters temperature has less influence on density than salinity, so that the vertical distribution of salinity and density are nearly parallel. Below about 100 m in the Eurasian Basin and 150 m in the Amerasian Basin, the temperature also rises.
- The layer immediately below the Arctic water mass is the Atlantic layer and ranges from about 150 to 250 m down to 900 m, has temperatures above 0°C (as high as approximately 3°C), and has a relatively uniform salinity of 34.9 to 35.1 ppt. This nearly isohaline water has nearly uniform potential density and provides a major heat source within the ocean. The source of this water is the North Atlantic, via the Norwegian and Greenland Seas.
- The layer from the Atlantic water to the bottom is occupied by "bottom water" with almost uniform salinities between 34.93 and 34.99 ppt. Its temperatures are nearly uniform also; in the Eurasian Basin they are −0.70°C to −0.80°C and in the Amerasian Basin from −0.30°C to −0.40°C. It constitutes 60% of the water volume in the polar basin.

Circulation

The general pattern of ice drift in the Arctic Ocean is well established from data collected by various drifting ice camps, ships, drifting buoys, and more recently satellites. Its movement (direction and speed) is mainly governed by wind and current. The relationship is complex, and empirically tested theories are not completely satisfactory. In many regions the wind is the dominant factor. Pure wind drift can be expressed by Zubov's rule of isobaric drift developed in the 1930s as a refinement of Nansen's observation of 1897. It states that ice drifts about 1/50th of the wind speed with a 28° deviation to the right (Northern Hemisphere). The influence of permanent currents is greatest near the Greenland Sea, where it may amount to 80% of the total drift. The proportion is not constant because the currents are subject to significant fluctuations in both speed and direction, both from year to year and from season to season. The gradient current is determined by the general atmospheric circulation over the Arctic basin, by the configuration of its shores, and by water exchange with marginal seas. Mean annual drift rates determined from Russian and American drifting ice stations vary from 0.2 to 2.6 nautical miles (nm) per day within the central Arctic Ocean. These are net rates measured along the general path of drift. The actual rates, which include all the short-term directional variations, raise the drift speed to between 1.2 and 4.0 nm per day. The ratio of net to actual distance yields a coefficient of meandering, can be used to compare drifts, and can serve as an index of deviation from the general direction of movement. It can give a better indication than net drift rate of the relative importance of wind and current influence. Higher ice drift rates have been recorded near the southern edge of the pack where the ice is often diverging, illustrating that the speed of drift is normally higher when the concentration of ice is less and the boundary more open. Differences in ice concentration may cause considerable variation, not only in rate of drift, but also in the angle of deviation from the wind direction.

The two dominant features of Arctic surface circulation are the Transpolar Drift Stream and the Pacific Gyre (Beaufort Gyre). The Transpolar Drift Stream is a wide region of moving pack ice of varying age, thickness, floe size, and surface roughness. It carries ice from the region of the East Siberian Sea across the geographic North Pole and down the east coast of Greenland, where it becomes the East Greenland Drift Stream. On the Siberian Side of the Transpolar Drift there are a series of anticlockwise circulations in the marginal seas. These cold and relatively shallow seas are principal contributors of ice into the Transpolar Drift Stream. During summer when many of these seas open up, higher ice concentrations (termed by the Russians as "ice massifs" and usually translated as "ice packs") remain in certain areas. They are found mainly in slack areas between diverging drift streams and are consistently associated with a coastline, which impedes ice movement.

The second major feature of the Arctic surface circulation pattern is the Pacific Gyre. It is generally a closed clockwise drift located between Alaska, the Canadian Archipelago, and the geographic North Pole. The center of the gyre is about 80°N and 140°W, which corresponds very nearly with the center of the mean atmospheric pressure anticyclone (Coachman and Aagard, 1974). Ice floes may remain for years in this gyral system; thus, it contains some of the oldest ice in the Arctic.

The boundary between these two systems is not clearly defined and can have seasonal fluctuations. Floes drifting north in the Pacific Gyre may enter the Transpolar drift stream and exit the Arctic Ocean. They could also drift into the area of very slow movement north of Ellesmere Island and Greenland. From here it may eventually rejoin the Gyre in the Beaufort Sea or leave the Arctic Basin by way of the channels of the Canadian Arctic Archipelago or the Lincoln Sea Drift between Ellesmere Island and Greenland.

General current circulation is shown in Figure 2.1.

Sound speed

Sound speed in the ocean or the water column is a function of temperature, salinity, and pressure. Figure 2.2 shows typical temperature and salinity profiles marking the Arctic, Atlantic, and Bottom waters. Figure 2.3 shows vertical profiles representative of six Arctic locations. The relationship between these variables in the central Arctic Ocean is such that sound speed is generally an increasing function of depth from the surface to the bottom. Positive sound speed gradients are typical in polar waters (Fig. 5.1). In the central Arctic, the profile structure has been found to be quite uniform as a function of location and season due to the relatively stable oceanographic conditions. Low-frequency (< 50 Hz) sounds can be transmitted great distances in this natural waveguide or sound channel by upward refraction in the water and repeated reflection from the ice cover. Higher frequency sounds are scattered by the ice bottomside roughness, considerably reducing transmission range.

Oceanographic conditions in the marginal sea ice zone exhibit wide horizontal and vertical variability. These conditions can change dramatically over a short time. Therefore, generalized regional and seasonal SVPs in these regions are often crude estimates of oceanographic conditions. The variation can be appreciated after examining marginal sea examples in Appendices A–M.

Temperature and salinity, plus descriptive oceanography for each Arctic sea, are discussed in Appendices A–M.

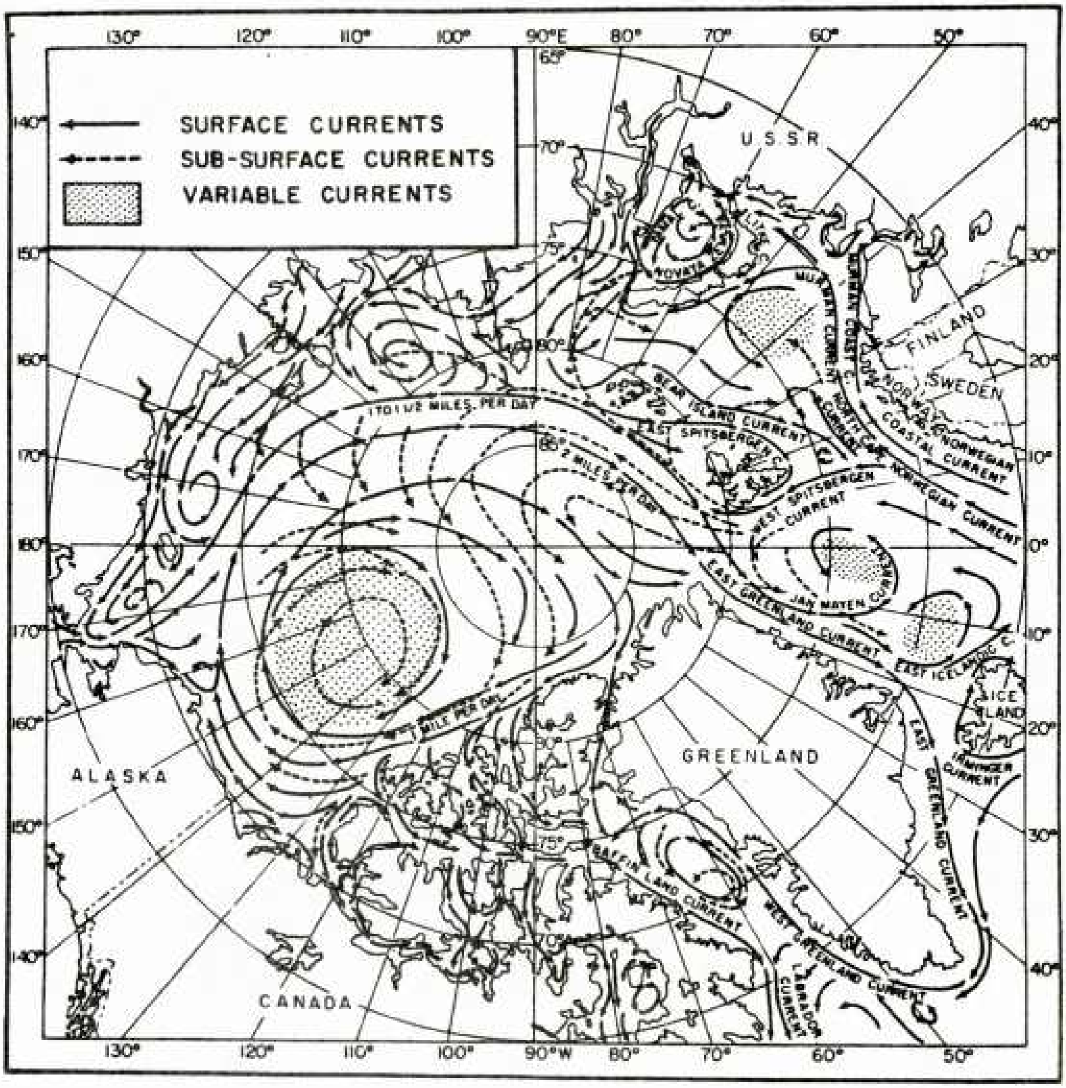


Figure 2.1. General Arctic circulation (from Fairbridge, 1966).

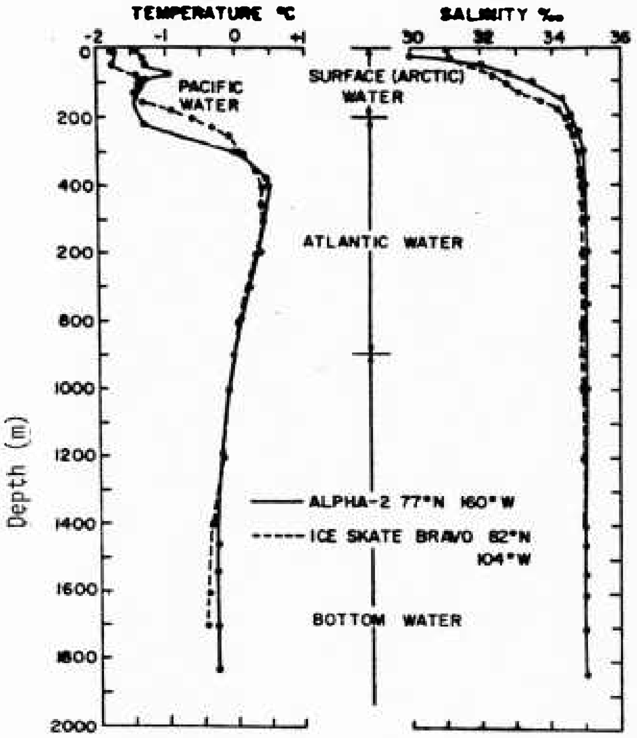


Figure 2.2. Surface (Arctic) water, Atlantic water, and bottom water are shown in profiles of temperature and salinity in the Arctic Ocean (from Fairbridge, 1966).

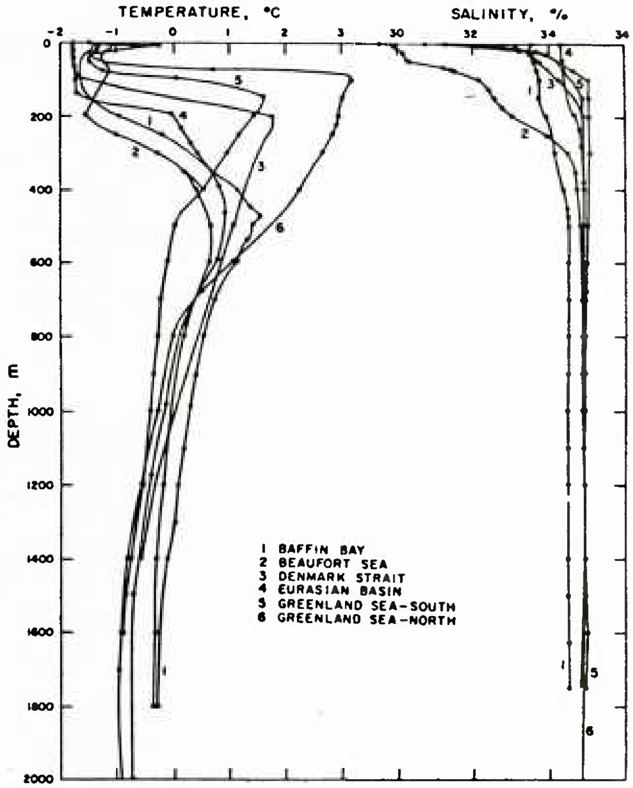


Figure 2.3. Vertical profiles of temperature and salinity at six Arctic locations (from Naval Arctic Manual, 1970).

Bibliography

Andersen, B. G., W. F. Weeks, and J. L. Newton (eds.) (1979). *The Seasonal Sea Ice Zone, Cold Regions Science and Technology*. Elsevier, v. 2, April.

Coachman, L. K. and K. Aagaard (1974). Physical Oceanography of Arctic and Sub-Arctic Seas. In *Marine Geology and Oceanography of the Arctic Seas*, Yvonne Herman (ed.), Springer-Verlag, New York.

Dunbar, M. and W. I. Wittmann (1963). Some Features of Ice Movement in the Arctic Basin. In *Proceedings of the Arctic Basin Symposium*, October 1962, Washington, D.C., The Arctic Institute of North America, pp. 90–104.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography*. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Kutschale, H. (1969). Arctic Hydroacoustics. Arctic, *Journal of the Arctic Institute of North America*, v. 22, n. 3, September.

Marginal Ice Zones (1983). *Journal of Geophysical Research*. v. 88, n. C5, pp. 2713–2972.

Naval Arctic Manual (1970). Oceanographic Atlas of the Polar Seas, Part II: Arctic, 1958. U.S. Naval Oceanographic Office, NSTL, Mississippi, ATP-17(A) COMTAC Publication, January.

Sater, J. E. (ed.) (1969). *The Arctic Basin*. The Arctic Institute of North America, Washington, D.C.

3. General climatology

Introduction

The Arctic climatic year consists of a long, cold winter followed by a few weeks of spring thaw, and a short, cool summer followed by a few weeks of fall freeze. Local climatic conditions are influenced by regional topography. For example, the varied elevation of the Brooks Range in Northern Alaska, the high elevation and vastness of the ice sheet in Greenland, the fjord coasts of Greenland and Labrador, the mountains of Verkhoyansk, and the land/water pattern in the Canadian Archipelago all have profound effects on local temperatures, winds, and precipitation.

There are great regional and seasonal variations in Arctic climatic conditions. Low temperature is the dominant feature and the Arctic region is often defined solely on the basis of temperature. The extreme Arctic or north polar climate is usually thought to be that in which the mean monthly temperature never exceeds freezing: this is the "ice cap" climate. The less extreme, but still severe, Arctic or north polar climate includes the areas in which the mean temperature for the warmest month is above freezing but below 10°C, and which have an average temperature below −3°C for the coldest month: this is the "tundra climate." The southern boundary of the region defined in this way approximates the northern limit of trees. The only northern areas of treeless tundra with a milder climate than these are the Aleutian Islands and parts of Iceland, Scotland, and Scandinavia. A practical working definition for regions in which the Arctic climate dominates is thus north of the tree line.

The Arctic's high latitude accounts for the long periods of daylight and darkness (Fig. 3.1) and for its low sun elevation, which results in a net radiational heat loss from the area. The high surface albedo characteristic of the persistent cover of snow and ice means that a high proportion of incoming solar radiation is reflected and that low temperatures are maintained. Arctic surface features are of relatively low elevation, which permits free atmospheric flow between the middle latitudes and the Arctic. Low temperatures and atmospheric exchange produce a stable stratified air mass in the north polar region. Eastward-moving frontal systems in which warm equatorial and cold polar air is mixed encircle the polar region.

Temperature

Temperatures of the Arctic region, which is essentially an ocean surrounded by land, are nowhere near as low as temperatures recorded in Antarctica, which is land surrounded by ocean. The mean annual temperature at the geographic North Pole is approximately −23°C. Minimum temperatures of −40°C are common, though extremes in excess of −50°C have been recorded. Temperatures rise as cloud cover and wind speed increase; maximum winter temperatures under overcast conditions without wind reach −25°C.

Summer temperatures are considerably higher than winter temperatures (Figs. 3.2 and 3.3). In most of the Arctic Basin mean temperatures over pack ice during

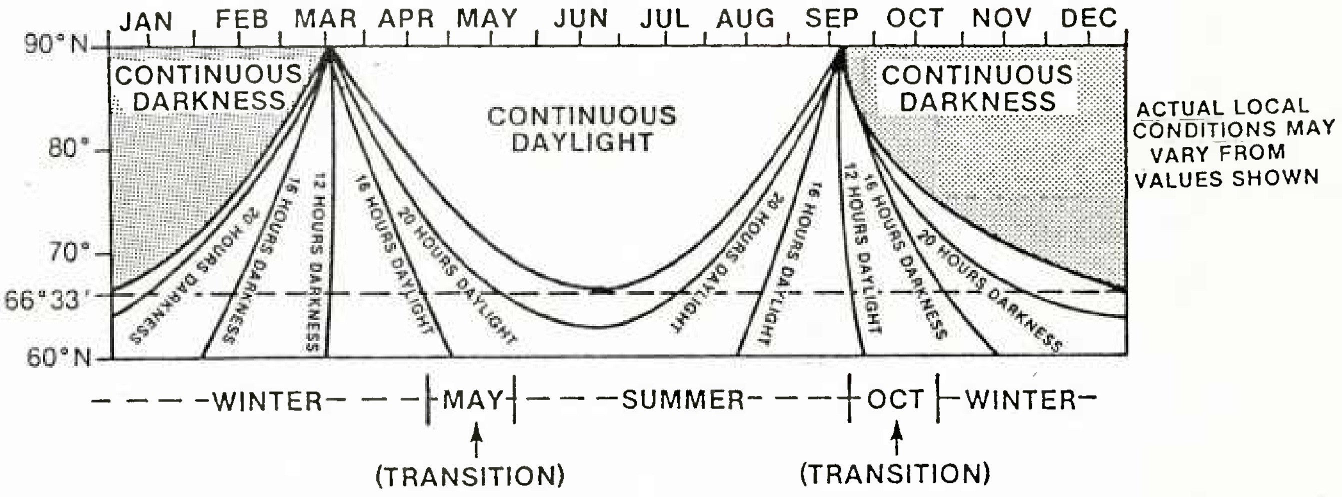


Figure 3.1. Latitude versus daylight distribution (Polar Regions Atlas, Central Intelligence Agency, May 1978).

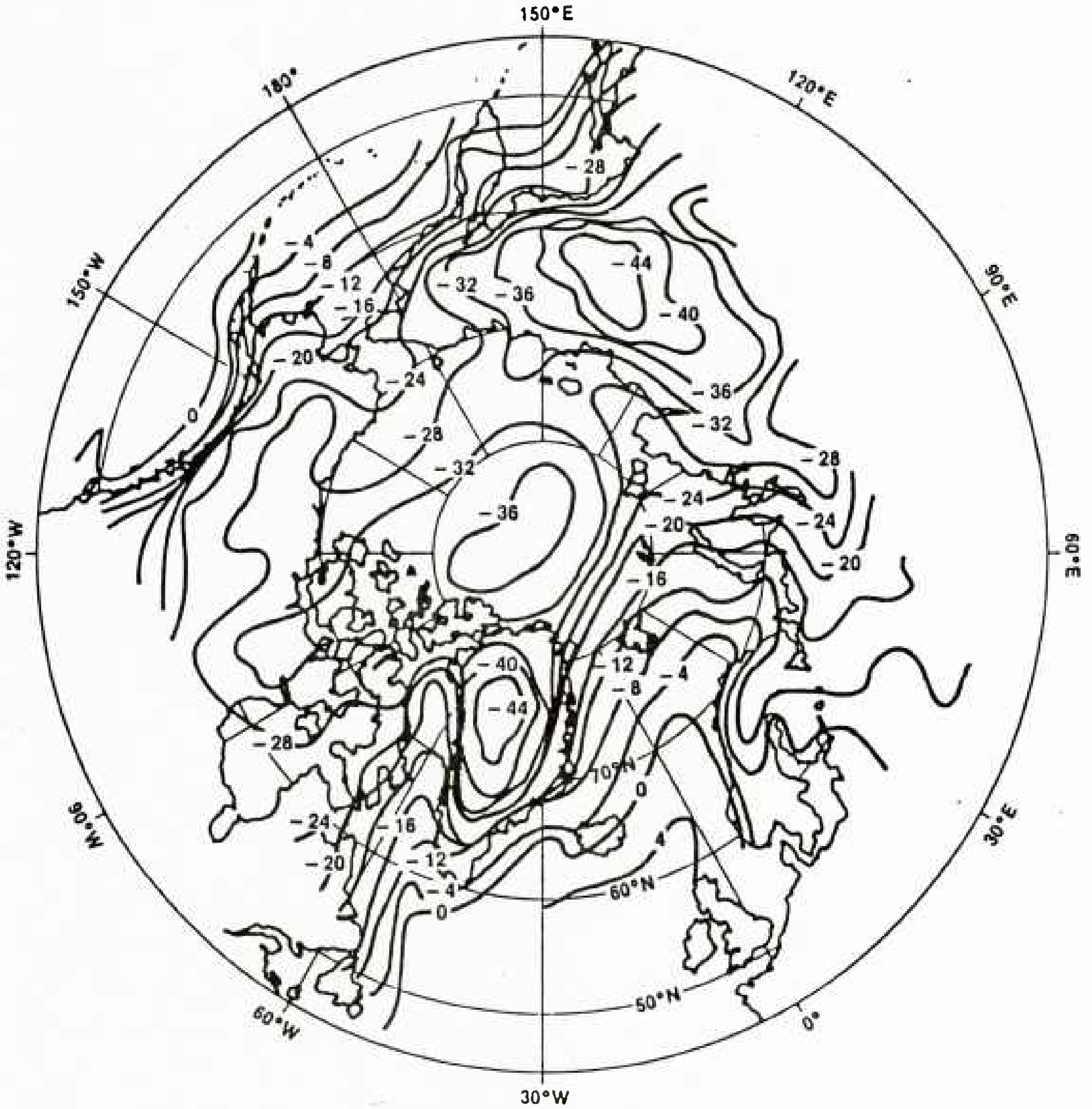


Figure 3.2. Mean air temperature (°C), January (Polar Regions Atlas, Central Intelligence Agency, May 1978).

summer are from 0° to 2°C with little deviation. A sharp air mass boundary commonly forms as warm air from inland areas is transported over icy waters and cooled. Warm air currents flow above the cooler surface air mass and have little influence on surface temperatures if winds are calm. However, Arctic surface temperatures increase with wind speed as a near linear function because of the mixing that occurs with the warmer air mass above the boundary.

Winds

Knowledge of wind direction, duration, and speed is critical in the Arctic because winds are primary drivers of sea ice dynamics, wind intensifies the feeling of cold, and winds limit Arctic travel when blowing snow restricts visibility. Wind speeds over the Arctic Ocean typically are 4 to 5 m/sec (8 to 10 knots). Because of the sharp air mass boundaries common in the Arctic, the surface layer is somewhat isolated from the faster moving air mass above. Even though the region is predominated by light winds, when strong winds occur they typically persist for periods from one to three days. High surface winds in the Arctic are usually associated with strong pressure gradients, but locally preferred wind directions can be dictated by topography. The Arctic has a wide variety of regional and seasonal wind characteristics, and specific information should be sought concerning local conditions when planning an Arctic mission. Specific sources of information are listed at the end of this section.

Conditions of low temperature and high wind produce the greatest heat loss and personal discomfort. For example,

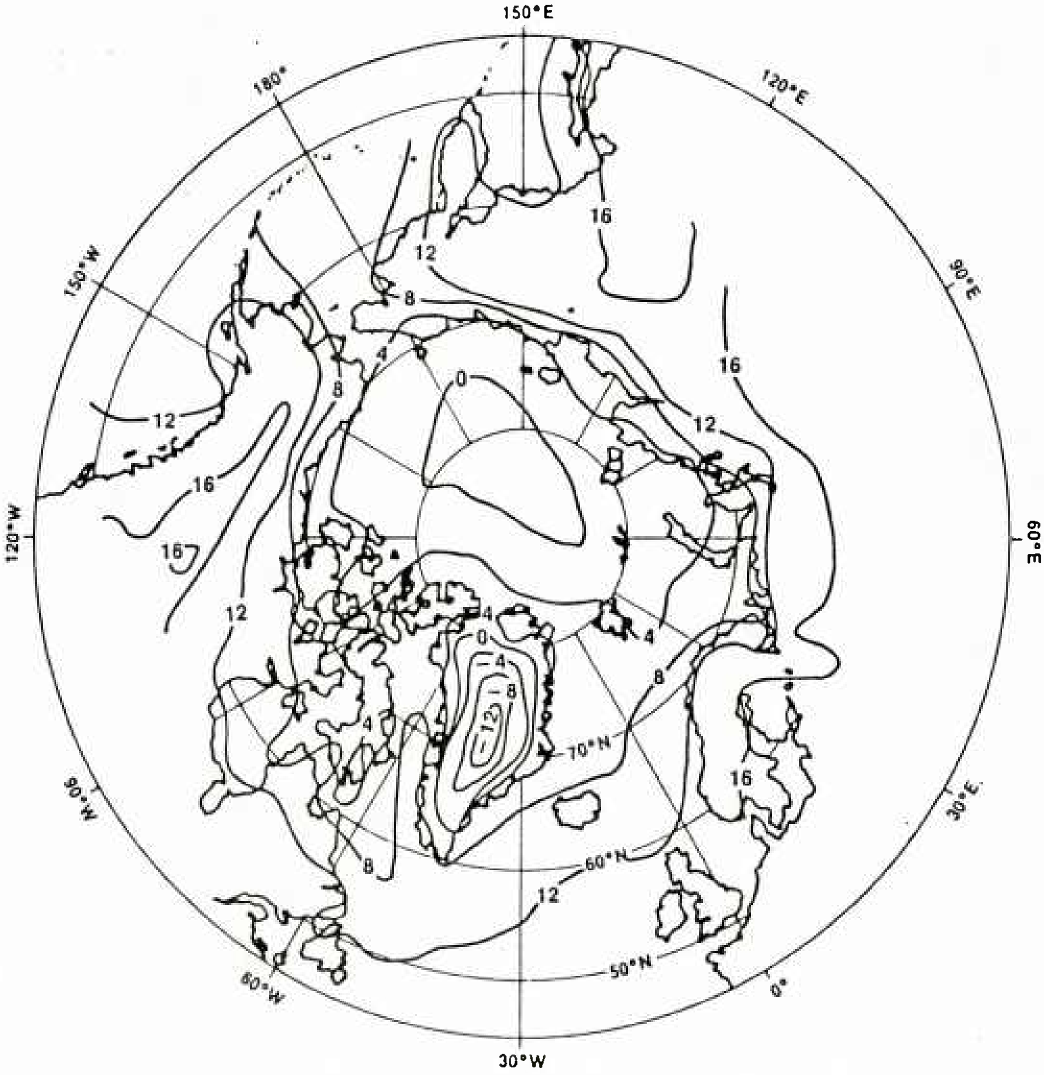


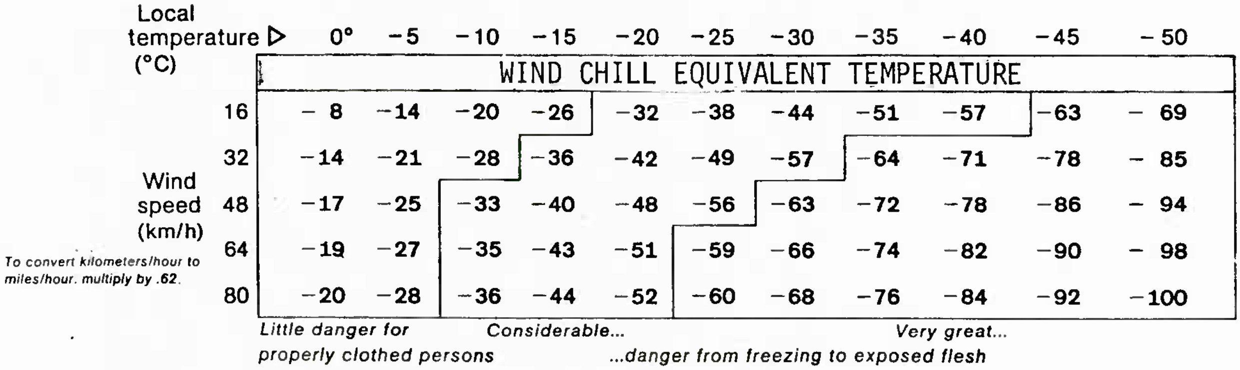
Figure 3.3. Mean air temperature (°C), July (Polar Regions Atlas, Central Intelligence Agency, May 1978).

a wind of 9 m/sec (about 20 mph) coupled with a temperature of − 15°C is just as effective in chilling a man as a temperature of − 40°C with winds of less than 1 m/sec. A chart of wind chill equivalent temperatures is shown in Figure 3.4. Physiologically, the coldest place in the Arctic is the interior of the Greenland Ice Sheet.

Precipitation

The concept that the Arctic is a region of deep snow is incorrect. Although snow cover is persistent throughout the Arctic and blowing snow is a common hazard, actual snowfall is so light that the region would be classified a desert or semi-desert were it located in more southerly latitudes. Average snow depths at the time of maximum cover in late March and early April range from 20 to 50 cm over the ice pack and from 40 to 70 cm over sub-Arctic land. Snow depth locally is irregular due to uneven terrain and wind drifting. Snow is swept from smooth surfaces and deposited in protected areas adjacent to ridges and hummocks. Duration of snow cover varies from about 10 months in the central Arctic to 7 months in the sub-Arctic.

Low temperature, characteristic of the Arctic, is the primary reason for low precipitation. Cold temperatures lower the absolute humidity and decrease the amount of available moisture. Accordingly, most precipitation falls as light rain in the summer when warmer temperatures occur. Mean monthly and annual precipitation data for specific Arctic locations are shown in Table 3.1.



Local temperature (°C) ▷	0°	−5	−10	−15	−20	−25	−30	−35	−40	−45	−50
Wind speed (km/h)	WIND CHILL EQUIVALENT TEMPERATURE										
16	−8	−14	−20	−26	−32	−38	−44	−51	−57	−63	−69
32	−14	−21	−28	−36	−42	−49	−57	−64	−71	−78	−85
48	−17	−25	−33	−40	−48	−56	−63	−72	−78	−86	−94
64	−19	−27	−35	−43	−51	−59	−66	−74	−82	−90	−98
80	−20	−28	−36	−44	−52	−60	−68	−76	−84	−92	−100

To convert kilometers/hour to miles/hour, multiply by .62.

Little danger for properly clothed persons *Considerable...* *Very great...* *...danger from freezing to exposed flesh*

Figure 3.4. Wind chill equivalent temperature (°C) (Polar Regions Atlas, Central Intelligence Agency, May 1978).

Table 3.1. Mean monthly and annual precipitation (mm) (1 mm = 0.0394 inches).

Place	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Yrs of Record
Jan Mayen	38	43	28	23	13	15	20	28	64	56	36	25	389	7
Bear Island	28	36	31	21	21	24	21	26	41	36	25	28	338	15
Green Harbour	33	31	28	23	13	1	18	20	23	31	25	41	299	14
Dikson Island	5	3	5	5	5	18	20	41	41	13	8	5	169	17
Cape Chelyuskin	3	3	3	3	3	2	28	28	10	8	5	3	99	22
Verkhoyansk	5	3	3	5	8	23	28	25	13	8	8	5	134	31
Wrangel Island	5	5	5	5	5	10	15	23	13	10	3	5	104	11
Barrow	5	5	3	3	3	8	23	18	13	15	8	8	112	25
Sachs Harbour	2	2	4	3	6	5	25	17	16	11	5	4	100	10
Cape Parry	7	7	5	18	10	22	23	36	30	28	9	9	204	5
Mould Bay	3	2	3	3	6	4	18	18	11	6	3	3	80	13
Holman	6	6	7	9	8	7	20	26	20	17	8	6	140	20
Coppermine	12	8	13	10	12	20	34	44	28	26	15	11	233	30
Cambridge Bay	8	4	6	5	6	13	25	25	16	13	10	6	237	32
Isachsen	2	1	1	4	8	4	21	20	18	9	4	2	94	13
Resolute	3	3	3	6	9	13	24	32	19	16	6	4	138	14
Eureka	3	2	2	2	3	3	14	12	11	7	2	2	62	14
Arctic Bay	8	5	7	6	8	12	20	25	22	17	8	6	144	24
Clyde	10	7	6	10	13	10	23	32	33	34	22	6	206	19
Alert	6	6	6	6	9	12	15	28	30	16	6	7	147	10
Cape Dyer	70	54	28	25	51	41	27	77	83	76	51	92	670	5
Thule	8	9	5	3	6	7	18	14	16	18	13	6	123	10
Upernavik	8	8	10	16	16	16	28	30	28	30	28	16	234	30
Prins Christians Sund	185	208	300	200	242	208	158	165	200	242	147	277	2532	5
Angmagssalik	79	76	74	58	40	46	36	58	76	120	71	69	803	30
Scoresbysund	48	36	23	36	10	20	38	18	46	25	28	51	379	5
Grimsey	15	18	13	10	18	36	36	58	51	64	46	23	388	13

Fog

A low, clinging fog is often seen during winter over leads and other areas of open water. The air becomes saturated almost immediately where open water is exposed because the water-vapor capacity of cold air is low. At temperatures below −37°C, water vapor sublimates on hydrocarbon molecules, which results in heavy fog in the immediate vicinity of large cities and major airports. Table 3.2 shows mean number of days with fog per month and year for various Arctic locations.

Operational weather

Probability of success for field measurement programs in the Arctic is greatly increased by extensive premission

Table 3.2. Mean number of days with fog per month and year.

Place	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Yrs of Record	Note
Jan Mayen	3	3	4	4	8	14	17	11	9	6	4	3	86	14	(1)
Green Harbour	*	1	*	*	*	3	4	3	1	1	0	0	13	7	(1)
Mossel Bay	2	5	4	5	3	2	11	3	5	1	1	2	44	9	(1)
Tromso	1	1	1	1	1	1	2	2	2	1	1	1	14	46	(1)
Bear Island	1	2	3	5	7	9	19	15	12	4	3	1	82	—	(1)
Vardo	*	*	0	*	1	3	7	5	1	*	*	*	17	44	(1)
Kola	1	*	*	*	1	1	3	4	2	1	2	1	16	10	(1)
Tikhaya Bay	6	7	9	9	9	10	15	16	6	5	4	5	100	10	(5)
Rudolfa Island	2	*	4	8	5	13	24	24	14	5	2	2	104	4	(5)
Vaigach Island	6	5	7	8	9	15	17	16	11	5	3	4	106	14	(5)
Yugor Strait	4	5	6	7	0	14	16	14	8	7	5	4	99	26	(1)
Dikson Island	4	4	5	7	7	15	20	16	11	5	3	2	99	18	(1)
Domashni Island	3	6	7	7	4	6	20	20	13	4	2	1	92	4	(1)
Cape Chelyuskin	2	4	8	8	8	13	24	24	13	6	5	2	117	7	(1)
Tiksi Bay	3	3	3	5	5	14	12	8	5	4	2	1	65	7	(1)
Verkhoyansk	3	2	1	*	1	*	1	5	4	1	2	4	24	9	(1)
Cape Shalaurova	4	7	8	8	8	15	18	15	6	3	3	6	101	10	(1)
Wrangel Island	2	2	3	5	7	12	14	14	6	3	4	3	75	13	(1)
St. Paul Island	1	2	2	3	5	7	10	8	3	*	*	*	42	28	(3)
Nome	3	1	1	1	3	5	3	2	*	*	1	2	23	15	(3)
Kotzebue	1	1	1	1	4	5	3	1	1	1	1	1	21	21	(3)
Barrow	2	1	1	3	8	13	13	11	5	4	2	2	65	20	(3)
Barter Island	1	1	2	3	8	11	15	15	11	3	3	1	74	13	(3)
Aklavik	1	1	*	*	1	1	1	1	2	1	1	*	11	20	(1)
Sachs Harbour	*	*	1	3	6	9	16	14	18	4	2	2	65	12	(1)
Cape Parry	2	3	2	3	9	12	12	11	8	3	2	2	69	10	(1)
Mould Bay	1	2	3	3	3	3	3	7	6	3	1	*	34	13	(1)
Holman	2	1	1	1	1	3	6	4	2	1	*	*	20	18	(1)
Coppermine	*	1	*	2	3	3	2	2	2	1	1	1	18	20	(1)
Cambridge Bay	1	2	1	2	5	3	3	4	3	3	2	2	30	18	(1)
Isachsen	1	2	5	5	3	3	6	8	8	5	2	1	49	12	(1)
Resolute	1	2	1	1	2	5	7	8	5	1	1	*	34	13	(1)
Eureka	1	1	1	1	*	*	*	1	2	2	1	1	10	13	(1)
Arctic Bay	*	*	1	1	1	*	2	2	1	*	*	*	8	20	(1)
Clyde	1	1	1	1	2	2	5	5	1	*	1	1	18	15	(1)
Alert	1	*	1	1	7	7	8	9	6	3	2	1	45	10	(1)
Cape Dyer	5	5	2	3	12	11	8	11	9	7	5	3	81	9	(1)
Thule	1	*	1	1	2	4	4	2	1	*	*	*	16	6	(2)
Upernavik	2	1	1	2	5	9	11	7	2	1	*	1	42	31	(4)
Angmagssalik	1	1	2	4	9	11	11	9	5	3	2	1	59	30	(1)
Scoresbysund	4	6	6	8	15	14	11	8	9	5	4	6	96	11	(4)
Grimsey	*	1	2	2	5	5	9	6	3	*	1	1	35	14	(1)

Notes: 1. A day with fog is defined as a day on which visibility was lowered by fog to less than 5/8 mile (1 km; ½ nm) for some part of the day.
2. As in Note 1, but visibility less than 1 mile (0.6 km).
3. As in Note 1, but visibility ¼ mile (0.4 km) or less.
4. As in Note 1, but visibility less than 3 miles (4.8 km).
5. Visibility criteria not specified.
6. * indicates less than 0.5 days.

planning and knowledge of and experience in the environment.

Certain general weather characteristics are common and can be regarded as "normal" for Arctic regions during specific seasons. A few of the more common conditions that will affect operations are listed.

- Winter

-Although midwinter is free of substantial snowfall, very light snow is common.

-Solar duration and angle is extremely limited and is a function of latitude and season.

-Although surface winds of storm velocity are infrequent, increasing winds intensify the feeling of cold and are responsible for blowing snow—a major

deterrent to winter travel. Drifting snow is often a hazard, commonly reaching blizzard conditions or producing the "white out" phenomenon where distance and direction are difficult to determine due to swirling winds.
  - General winter conditions are darker, dryer, and colder than summer conditions.
- Summer
  - Although precipitation is light, prolonged periods of moderate rain occur.
  - Increased solar duration and intensity significantly affect the environment and surface moisture.
  - Low-stratus clouds and advection fog are very common in the warmer months because of the passage of warmer air masses over the cold ice surfaces.
  - General summer conditions are lighter, wetter, and warmer than winter conditions.

Summary

The information presented here is designed to provide a general overview of climatic and meteorologic conditions found in the Arctic. When planning a mission, operation, or experiment, one is encouraged to contact the following sources for specific guidance.

U.S. Department of Commerce
Natonal Oceanic and Atmospheric Administration
Rockville, Maryland

Provides synoptic surface and upper air charts, forecasts, summaries, and predictions for areas throughout the Arctic.

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Climatic Data Center
Asheville, North Carolina

Provides climatological data from reporting stations in Alaska, Canada, Greenland, Iceland, and northern Europe.

U.S. Navy
NOAA Joint Ice Center
Suitland, Maryland

Provides reports of current ice conditions in the Arctic and adjacent seas, 30-day summaries, forecasts, and seasonal outlooks. Specific information is available upon request.

U.S. Navy Fleet Numerical Oceanography Center
Monterey, California

Provides sea ice predictions of distribution, drift, and thickness.

In addition to these, regional centers are located in Anchorage, Alaska (NOAA), Toronto, Canada (Meteorology/Sea Ice), and Iceland (Navy Fleet Weather).

Bibliography

Byers, H. R. (1974). *General Meteorology*. McGraw-Hill, Inc., New York.

Central Intelligence Agency (1978). *Polar Regions Atlas*.

Central Intelligence Agency (1983). *Polar Regions Atlas*. May.

Naval Arctic Manual (1970). *Oceanographic Atlas of the Polar Seas, Part II: Arctic*. U.S. Naval Oceanographic Office, NSTL, Mississippi, ATP-17(A), COMTAC publications, January.

Rey, L. (ed.) (1982). *The Arctic Ocean*. John Wiley and Sons, Inc. New York, p. 135–161.

Sater, J. E. (ed.) (1969). *The Arctic Basin*. The Arctic Institute of North America, Washington, D.C.

4. Comparison of U.S.—U.S.S.R. Arctic programs

Introduction

The NORDA Polar Oceanography Branch has conducted a quick-look assessment of U.S. and U.S.S.R. Arctic programs. The purpose is to assess the potential and present capabilities for naval operations in Arctic waters. Available data bases, pertinent U.S. sponsors, principal investigators, and NISC/DIA reports provided the primary sources of information.

Conclusions

U.S. efforts in the Arctic have been sporadic and uncoupled. Only modest support has been available to carry out work in a very inhospitable environment in which extraordinary costs are common. In addition, support for this work has been decreasing in real terms, forcing a reduction or elimination in manned operations at sites such as the Naval Arctic Research Laboratory at Barrow, Alaska, and ice stations. In addition, there is a shortage of Arctic-trained personnel and an unsatisfactory situation with regard to icebreakers, Arctic-dedicated aircraft, and submarines. At present, we have no operating ice stations and recent drift station activities have been infrequent. As a result, the U.S. base of knowledge for assessing Arctic operations appears somewhat limited.

By comparison, U.S.S.R. Arctic research activities seem to have been sustained at a high level since 1920. The Eurasian Basin has been investigated almost exclusively by the Soviets using drifting ice stations, spot landings, and drifting automatic meteorological stations. Soviet activity has included manned and unmanned Arctic research stations, a large number of Arctic expeditions, and three nuclear and numerous diesel-powered icebreakers. These efforts give the Soviets a significant superiority in the Arctic and adjacent seas. However, even though the Soviets have devoted much more attention to Arctic research, a surprisingly small amount of scientific information appears in the open literature, apparently due to a policy decision in the mid-1970s. Available indicators relative to research in the Soviet Union suggest a much more dedicated effort than in the United States and a broader base of knowledge from which to assess strategic utility and survivability.

Summary

General: The vast Soviet Arctic coastline, the Northern Sea Route (NSR), and the northern location of Murmansk (the largest military complex in the world) have all contributed to the need for Soviet Arctic research to improve Arctic weather and sea ice forecasting. Since initiation in 1920 of Soviet Arctic research, three major programs supported by many ministries, institutes, and laboratories have been developed: the NSR Program, the Manned Drifting Ice Station Program, and the High Latitude Airborne Expeditions.

The development of a dedicated U.S. Arctic research program and the establishment in 1947 of the Arctic Research Laboratory (Naval Arctic Research Laboratory, NARL) near Pt. Barrow, Alaska, are principally related to the establishment of the Office of Naval Research (ONR) in 1946. Unlike the U.S.S.R., the U.S. has not established a central organization to plan and execute research programs for the Arctic. Sections of noncollaborating agencies are involved in polar research studies such as universities, Navy, Army, Air Force, National Science Foundation, United States Geological Survey, National Oceanic and Atmospheric Administration, Coast Guard, oil companies, and many sectors of private industry in support of civilian and military efforts.

Ice Stations: Soviet commitment in Arctic research is evident by their adherence to the 1958 policy announcement that no less than two drifting ice stations will be maintained at all times. The Soviets have established 26 semipermanent drifting ice stations since 1937, and NP-25 and NP-26 were still in operation as of April 1984. Some of these ice stations have been inhabited for protracted periods of time, enabling continuous geophysical observations. The operation of 26 drifting ice stations has resulted in excellent geographic coverage for the Soviets in both the Eurasian and Amerasian Basins of the Arctic Ocean.

In addition to these semipermanent stations, 32 High Latitude Airborne Expeditions (HLAE) to conduct geophysical observations have been completed since 1941. These expeditions, which last between two and three months, have increased the density and geographic distribution of Soviet scientific observations in the Arctic regions.

U.S. ice station activity has been much more sporadic than the Soviets and has been confined largely to the Amerasian Basin. Ice station research activities were initiated by the U.S. Air Force in 1952 after discovery of the drifting ice island, T-3. The International Geophysical Year (1957–1958) further stimulated polar research by the United States and resulted in the establishment of several ice research stations in the late 1950s.

During the early 1960s ARLIS II, an ice island, provided the major drifting platform for U.S. efforts. T-3 remained in operation on a limited basis until 1972. Since then, U.S. ice stations have been established primarily for the purpose of conducting specific experiments in designated areas of interest.

Icebreakers: The Soviets have a superior surface naval capability in the Arctic and adjacent seas. The Soviet Arctic fleet has been very active in Arctic research and includes three nuclear and numerous diesel-powered icebreakers of various sizes. The Soviets also have extensive experience with the U.S. Wind Class icebreakers, which they operated under a loan agreement from the mid-1940s through the early 1950s.

The entire Navy's icebreaker fleet was transferred to the U.S. Coast Guard during late 1965 and 1966 to allow the Navy to free more personnel for combat tasks. Five Wind-Class icebreakers have been decommissioned, and only the NORTHWIND and WESTWIND are still in service. Two Polar Class icebreakers were commissioned in 1976 and 1977. The primary duty of these vessels is icebreaking, but they were also designed to function as research vessels and can accommodate up to 10 scientists. The U.S. has no nuclear-powered icebreakers.

Submarines: Since the early 1930s Soviet submarines have maintained a nearly continuous, large-scale measurement program covering much of the Arctic Ocean. Underice operations were severely limited by conventionally powered submarines until June 1962 when the submarine LENINSKIY KOMSOMOL sailed under the ice to the North Pole.

Well over half of the Soviet SSBN Fleet along with other types of Soviet submarines operate from bases in the Arctic.

The recent deployment of the Soviet Typhoon Class submarine in the Arctic as an Arctic SLBM platform has increased the threat of Soviet Arctic operations.

The first extended U.S. underice submarine operations were made in the Chukchi Sea in 1947. In 1957, the USS NAUTILUS (SSN571) conducted a 1383-nm operation under pack ice, which opened a new era introducing nuclear submarine operations in the Arctic. The U.S. has typically conducted a submarine Arctic exercise every year since 1961, alternating between the Atlantic and Pacific sides of the Arctic Ocean.

Satellites: The Soviet experimental program for studying the earth's natural resources from unmanned spacecraft began with the METEOR satellites equipped with multispectral television cameras. From 1974 to 1979 four of these satellites were launched. The primary sensor in this program was an informational radio and television complex (RTVK), which consisted of two low- and medium-resolution multichannel scanning units. In addition to the RTVK, which had operational application, seven instruments operating in the visible, infrared, and microwave bands were tested. The RTVK information was used to evaluate sea ice conditions, which included ice field distribution and movements, ice age and concentration, and detecting free-floating icebergs. A second generation METEOR spacecraft, launched in 1980, had similar sensors with spatial resolutions of up to 80 m. COSMOS 1076 and COSMOS 1151, launched in 1979 and 1980, were the first Soviet satellites dedicated to oceanographic research, as well as to atmospheric studies. A multichannel passive microwave radiometer was used to study sea ice characteristics. The radiometer viewed nadir with spatial resolutions ranging from 18 to 85 km. INTERCOSMOS 21, launched in 1981, was also intended for ocean research. The INTERCOSMOS series also serve as relay stations for transmitting data from buoys and research ships to ground stations.

The U.S. satellite environmental sensing program began in the early 1960s with the TIROS and ESSA series. These meteorological satellites employed vidicon systems that revealed cloud cover structure and large-scale ice features. In later generation satellites (such as NOAA, LANDSAT, and DMSP), scanning high-resolution radiometers were used. The sequential imagery from LANDSAT, with a resolution of 60 to 80 m, could be used to track drifting ice floes. The wide swath (2350 km) of the NOAA Very High Resolution Radiometers (VHRR) and the daily repeatability enable monitoring of large-scale pack ice behavior.

During the past decade microwave systems on satellites have been emphasized. The NIMBUS 5 and 7 satellites employ passive microwave systems with optimum resolutions of 25 km. Although the poor resolution makes interpretation difficult, these systems have been effective in mapping variations in the large-scale extent of sea ice in polar regions. SEASAT-A and GOES-3 were equipped with radar altimeters that could be used to locate the ice edge within a few kilometers. The U.S. Navy GEOSAT has a similar altimeter. SEASAT-A, which failed after 3½ months, had a synthetic aperture radar with a 100-km swath width with 25-m resolution. Many significant ice/water features could be identified over periods of weeks.

5. Arctic acoustics

Introduction

This discussion of Arctic acoustics is divided into three parts: propagation, reverberation, and ambient noise.

Arctic propagation

Two features that distinguish the Arctic environment and most strongly influence underwater sound are the ice cover and the sound speed structure in the water. Arctic seas are generally cold on the surface and, for much of the year, are cold enough to support a heavy ice cover. Large ice floes sometimes exceed 10 m in draft, and keels of pressure ridges may extend deeper than 40 m. One of the most characteristic properties of the Central Arctic waters is that the typical sound velocity profile has a positive velocity gradient. A sound velocity profile typical of that found in the Central Arctic is shown in Figure 5.1. Since negative sound velocity gradients have not been reported as occurring under the permanent ice pack, the existence of shadow zones is unlikely. The positive gradient results in upward refraction and half-channel propagation. In the summer, a weak near-surface sound channel sometimes appears (as shown in Figure 5.2), and is caused by the effects of melting ice and partially open water. Long transmission distances (greater than 700 miles) are possible for low-frequency sounds (below 100 Hz) because of the upward refraction of the sound wave and repeated reflections from the underside of the ice canopy. This upward refraction is shown in the ray diagram of Figure 5.3.

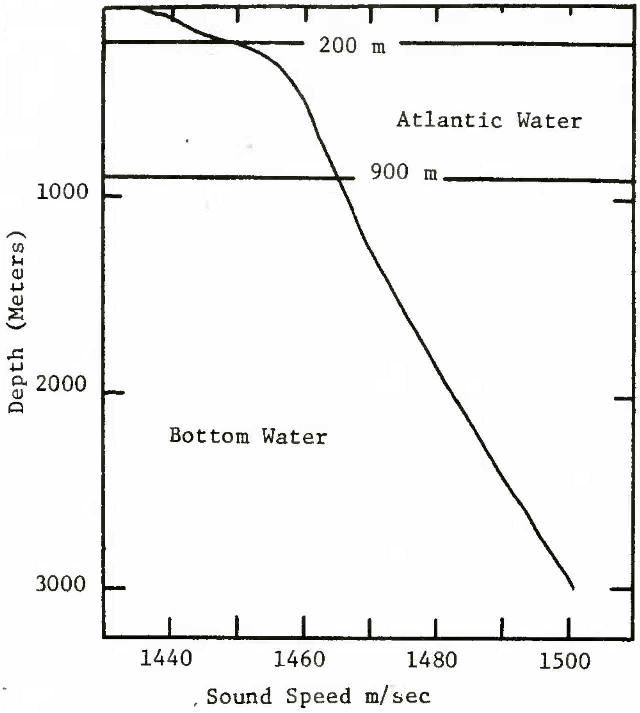


Figure 5.1. Typical Arctic Basin sound speed profile (Orr, 1975).

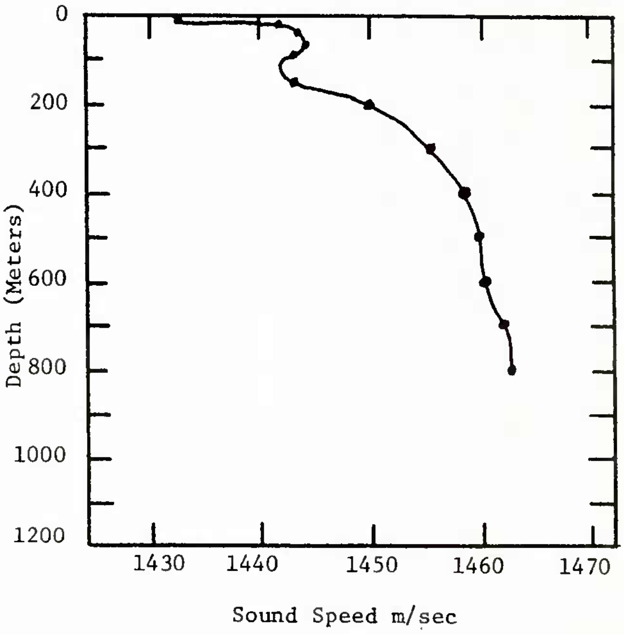


Figure 5.2. Typical summer sound speed profile in the Arctic Basin (Orr, 1975).

Under an ice cover, the combination of upward refraction and downward reflection from the rough underice surface creates unique propagation effects. Both high and low frequencies are rapidly attenuated, the high frequencies by reflection losses from the ice cover, the low frequencies by the fact that they are not effectively trapped in the sound channel. In the Arctic, the best propagation has generally been found to occur in the 10–60 Hz range. This is source and receiver depth dependent. Buck (1968) found the optimum receiver depth to be about 200–300 ft with detection ranges (FOM = 100 dB) of 300 to greater than 700 nm for shallow to deep sources. Within the passband, dispersion occurs. Wave packets of different frequencies are observed to have different group velocities, with low frequencies traveling faster than high frequencies. In addition, the time stretching that is a dominant characteristic of sofar signals also occurs. Because of these two effects—dispersion in both frequency and time—a distant explosion in Arctic waters is received as a long,

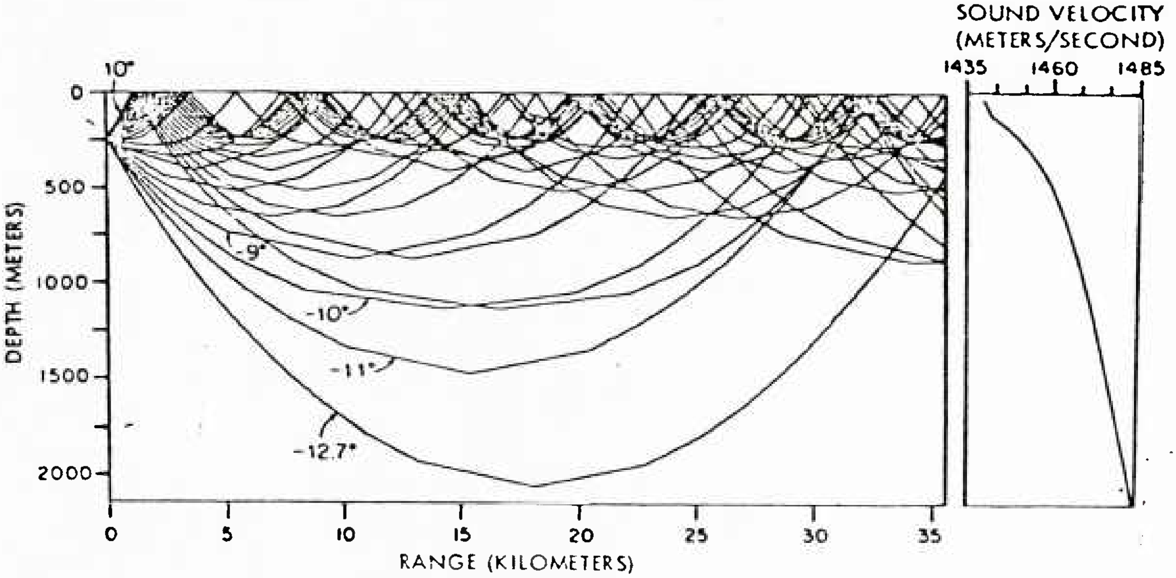


Figure 5.3. Typical sound speed profile and corresponding ray diagram for sound propagation in the Arctic Ocean (Urick, 1983).

drawn-out pulse of several seconds duration, with frequencies near the lower end of the passband appearing at the beginning of the signal and higher frequencies appearing at the end (Urick, 1983).

Buck (1968) summarized a number of measurements of transmission loss (his and others) in the ice-covered, upward-refractive Arctic, principally during the years 1960–1965. The results are shown in Figure 5.4. These curves show the average measured transmission loss in the Arctic at a number of frequencies, based on the available data; the standard deviation of the various data points from the smooth curve is shown for each frequency.

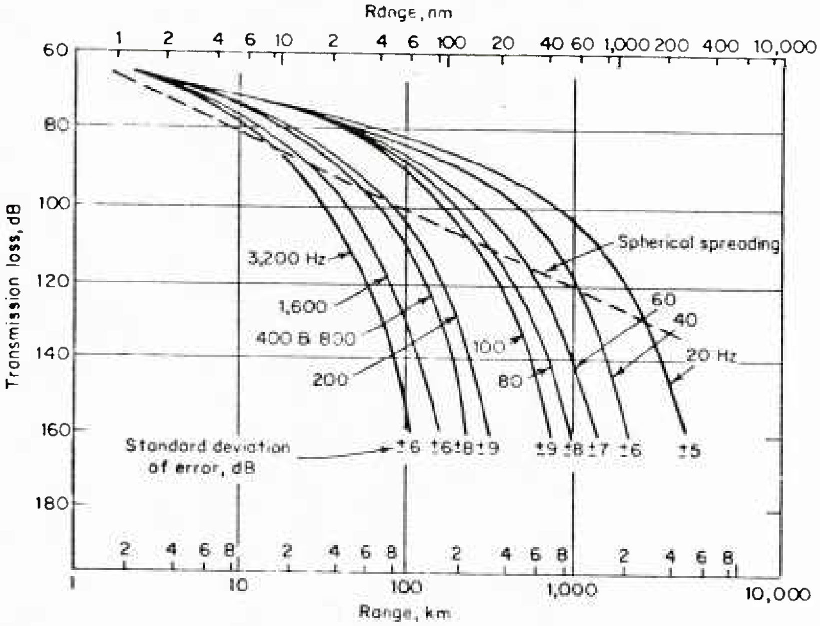


Figure 5.4. Average transmission loss in the Arctic (Urick, 1983),

The dashed line shows spherical spreading (*TL = 20 log r*). It is evident that the transmission in the Arctic degrades rapidly with increasing frequency above 20 Hz. It is better than it would be in the free field (i.e., with spherical spreading) out to some range, and is poorer beyond. This peculiarity is the result of opposing forces on the propagation. At short and moderate ranges, ducting improves the transmission; at long ranges the repeated encounters with the underice surface degrade it. These same effects occur in shallow-water ducts as well. Subsequent data confirming the validity of the curves in Figure 5.4 have been reported by Bradley (1973) from work done in a marginal ice zone (MIZ) east of Greenland.

Pedersen (1983) presents four possible loss processes that may account for the rapid increase in loss with range under the ice canopy. The present assumption is that this loss is due principally to scattering off the water-ice interface. If the sound is scattered into angles steeper than 20° with respect to the horizontal, the energy could be either backscattered or intersect the ocean bottom and be dissipated by the bottom sediments. Second, energy transfers into the ice canopy. Better signal-to-noise ratios have been reported for a seismometer frozen into the ice surface than for a 100-ft hydrophone at low frequencies. Third, compression and shear wave attenuation in the ice canopy may contribute, particularly in combination with scattering, i.e., energy scattered into steeper angles may be eventually dissipated in the ice canopy. Fourth, it has been noted that the absorption of sound in sea water increases with decreasing temperatures. For example, at 400 Hz it has been reported that attenuations below 4°C are about twice the value at 25°C.

Pedersen (1983) also has presented three reasons why bottom-bounce propagation paths are important. First, the high reflection losses associated with the ice canopy increase the channel loss. Hence, a lower total loss configuration may occur with a few bounces off the bottom and surface compared to many bounces off the surface and none off the bottom. Second, the steeper angles of bottom-bounce paths will tend to make the effects of ice keels smaller. Third, the huge half-channel may be good for detection, but the associated complicated multipath structure will make passive localization by such methods as RAPLOC impossible. Passive localization may have to employ bottom bounce paths.

No propagation models are presently applicable to the MIZ. However, NORDA is developing oceanographic models for these areas. The environment in the MIZ is so complicated and rapidly changing that it is questionable whether environmental parameters could be obtained for application to operational conditions even if an adequate acoustic model existed. Since the MIZ is not a specific, invariant, geographically bounded area, but is a dynamic region where the presence or absence of ice cover is variable, it will probably be necessary to go to some sort of statistical modeling for both oceanographic and transmission models. Thus, application to operational conditions is still uncertain at this time and in the near future.

Ice-free regions in the Arctic adjacent to the MIZ may pose some special problems. Propagation models, designed for temperate environments may need to be modified for the ice-free Arctic regions. In the Arctic the problem of many surface reflections is exaggerated, since losses are often increased by the presence of a strong positive thermocline, which produces a steep sound speed gradient. This steep gradient shortens the ray loop length and causes more reflections from the ocean surface. Thus, better values of surface reflection loss will be needed. Positive thermoclines occur in many sub-Arctic areas, as well as under the ice cover itself, and ray theory may provide an excellent approach for large positive-gradient ducts.

Coupling effects between multiple ducts may also be useful. Figure 5.5 illustrates a double duct measured in the fall, which is located about midway between Greenland and Spitsbergen. In this example, the double duct consists

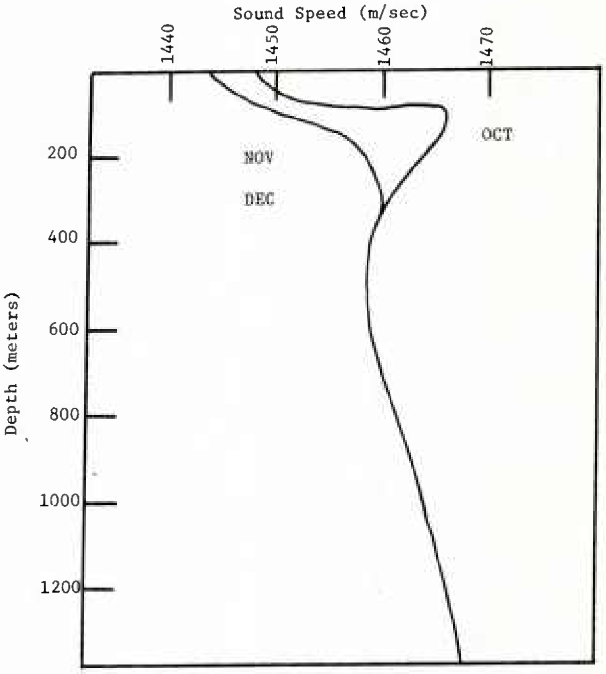


Figure 5.5. Sound speed profile from the Greenland Sea (Pedersen, 1983).

of a surface half-duct overlying a refractive duct. These double ducts also occur under the ice canopy in the Bering Sea in winter. In other areas double ducts consisting of two refractive ducts exist. Double ducts appear to be prevalent between North Cape, Norway, and Spitsbergen. The coupling between double ducts is strongly frequency dependent.

For horizontal distances greater than several skip distances with respect to the bottom-limited array, Arctic waters generally act like surface-bounded sound channels with very rough surfaces. Sound transmission, for hundreds of kilometers, can usefully occur for frequencies below 50 Hz where acoustic wavelengths exceed the dimensions of underice roughness. Long-distance passive detection, therefore, depends upon targets that can generate underwater energy in frequencies less than 50 Hz.

Reverberation

Reverberation is a time-dependent noise occurring in a sound receiver shortly after the emission of an outgoing signal from an underwater projector. It is the sum of all the false signals scattered back from the volume and the boundaries of the sea (*Naval Arctic Manual*, 1970).

Reverberation in the Arctic is a serious problem. It is so serious that little consideration is given to active sensors. Torpedoes, which use active homing, have had difficulties in the past because of so-called ''ice capture,'' which is a direct result of the reverberation (Anti-Submarine Warfare Systems Project Office, 1977).

Volume reverberation in the Arctic is not appreciable due to a decreased scattering layer concentration compared to the open ocean. The scattering layer, which is believed to be caused by marine life, has been found to exist in the Arctic at depths of 160 to 650 ft, which is considerably more shallow than the open ocean. The scattering layer exhibits an annual rather than a diurnal cycle like the open ocean. The layer occurs at moderate depths due to the weak light levels under the ice, and is present in the summer when sunlight prevails. In the winter, when it is dark, the organisms are near the surface and the layer disappears. The layer sometimes splits into two or three parts, just as it does in the open ocean. Volume reverberation due to the scattering layer is low compared to the 40 dB re (1 μPa)^2/Hz level usually observed in the open ocean and is quite insignificant compared to ice scattering.

Sea ice is the dominant cause of reverberation noise in Arctic regions. For undeformed first-year ice, the reverberation noise for frequencies above 3 kHz is about equivalent to that expected from an ice-free sea surface with a 30-knot wind blowing. In broken pack ice in the springtime this noise can increase by 20 dB. In any case, a target with dimensions of the order of the mean amplitude of the underice irregularities may be completely buried in the reverberation noise at all ranges (*Naval Arctic Manual*, 1970).

Because of the variation in the underice surface, the scattering strength measurements as a function of grazing angle, taken by different observers, demonstrate different characteristics. When the underice surface is relatively smooth, the scattering strength increases with grazing angle as in the open ocean. When ridge keels are present, the low grazing angle sound wave strikes these in a near-normal incidence and high reflections occur. Then as the angle becomes greater, less reflection takes place.

Figure 5.6 shows the results of measurements from the backscattering strength of the ice-covered sea for two Arctic locations at different times of year. The spring pack ice measured by Milne (1964) during late April and early May was described as consisting ''largely of broken and pressure-packed one-year ice intermixed with broken frozen leads.'' The summer polar ice, for which much smaller backscattering strengths were obtained by Brown (1964) during September, was not described, but was probably less irregular in its bottom contour. Included in Figure 5.6 are curves of the backscattering of the ice-free sea at a 25-knot wind speed. Both sets of data for underice scattering, although discordant, show an increase of scattering strength with frequency and grazing angle. Certain other data (Mellen and Marsh, 1963), however, indicate an absence of a frequency variation, and may be characteristic of a third kind of underice topography. The engineer, accordingly, has only fragmentary data available on which to base a prediction of the reverberation to be expected under an ice cover, although it is clear that backscattering

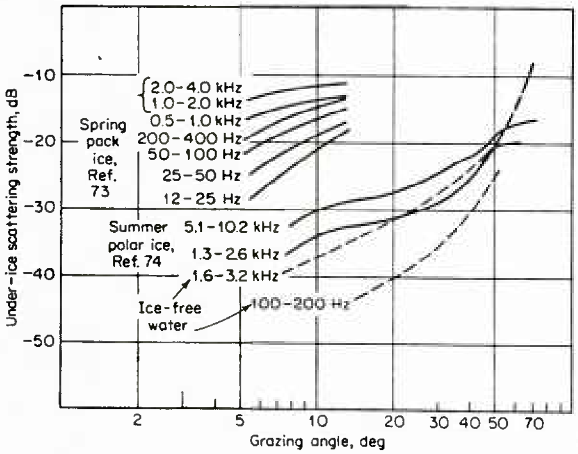


Figure 5.6. Scattering strengths of an ice cover (Urick, 1983).

strengths higher than those for the ice-free sea at low and moderate wind speeds must prevail.

In contrast with Arctic seas, wave motion in ice-free seas adds to the sound speeds of signals reflected from them. Thus, sea wave motion produces Doppler frequency broadening of reverberation signals that can mask Doppler frequency shifts of targets in motion. Under sea ice, however, such frequency shifts of echoes from moving targets could possibly be observed within the higher reverberation noise.

Reverberation noise can also be minimized by using highly directional sources and receivers to exploit optimum ray paths. Such paths could provide time discrimination between echoes and reverberations for targets spatially separated from the ice surface.

Ambient noise

Ambient noise is a composite noise from all sources, irrespective of sonic devices and platforms used to observe it. Ambient noise under sea ice has been separated into the following categories (*Naval Arctic Manual*, 1970):

1. Above 50 kHz, a major noise source is thermal noise, which is caused by the agitation of water molecules.
2. Noise originated at the ice-covered sea surface.
3. Biological noise from soniferous fauna.
4. Man-made noise from underwater explosions, ships, and other sources.
5. Low-frequency, naturally occurring noises caused by earthquakes, microseisms, and standing and propagating waves on ice-covered seas.

Categories (4) and (5) are important noise sources at low frequencies (greater than 30 Hz) because of the low pass filtering effect of the rough ice canopy. An explosive charge set off hundreds of kilometers away can produce noise that is observable for hours in the Arctic Basin. Similarly, other sources of low frequency energy can raise the background noise because of their ability to travel long distances with relatively little attenuation (*Naval Arctic Manual*, 1970).

The ice cover is the major source of noise in the Arctic. Ice noise, which is more important between frequencies of 100 Hz and 30 kHz, will be more local in origin than the lower frequency noises. The level and character of the ice noise is highly variable and depends on ice conditions, wind speed, snow cover, and air temperature changes.

Ice noises may be caused by ice fracturing, floe collisons, and other bumping and grinding actions of the ice due to wind and current stresses; thermal cracking due to tensile stresses in the ice associated with decreasing air temperatures; and wind-driven snow impinging on the ice surface.

Wind noise, caused by wind turbulence, is also present and is more prominent under a noncontinuous ice cover than it is under a continuous ice cover. When the ice is not continuous, noise levels 5 to 10 dB higher than those measured at the same sea state in ice-free waters have been observed (Urick, 1983).

Ambient noise under the pack ice cover is highly variable in time. Wind stress applied to the ice is immediately manifested as a change in ambient noise. Figure 5.7 shows measured spectra parameterized according to wind speed.

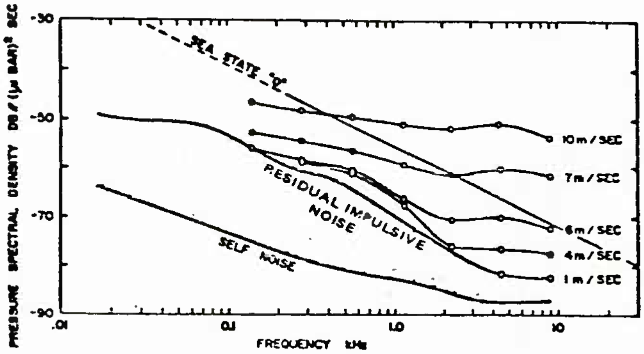


Figure 5.7. Pressure spectra of underice noise for different wind speeds, recorded during air-warming trends (JHU/APL, 1982).

Thermal stress in the ice resulting from changes in local temperatures is also an important noise-generating mechanism. Figure 5.8 shows samples of noise spectra from data taken during periods of cooling with no wind. Sample A is a residual ice noise observed in a long warming trend (Johns Hopkins University/Applied Physics Laboratory, 1982).

An additional natural sea noise is made by icebergs as they melt. Numerous tiny bubbles of air entrapped under pressure are suddenly released as the iceberg melts, and the air rushes out with a sharp crack of sound. This kind of noise has been found to have a flat (i.e., white noise) spectrum of such intensity that icebergs may be the dominant source of noise in areas where they are prevalent and are actively melting.

Predictions of the spectra and amplitude distribution of the noise to be expected under an ice cover cannot be made at this time. However, very low levels, well below

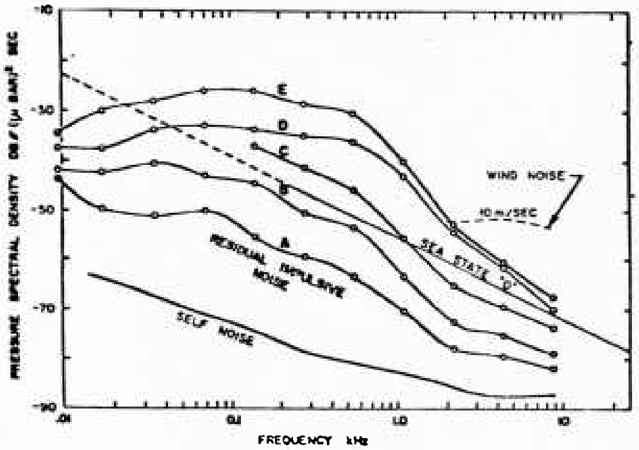
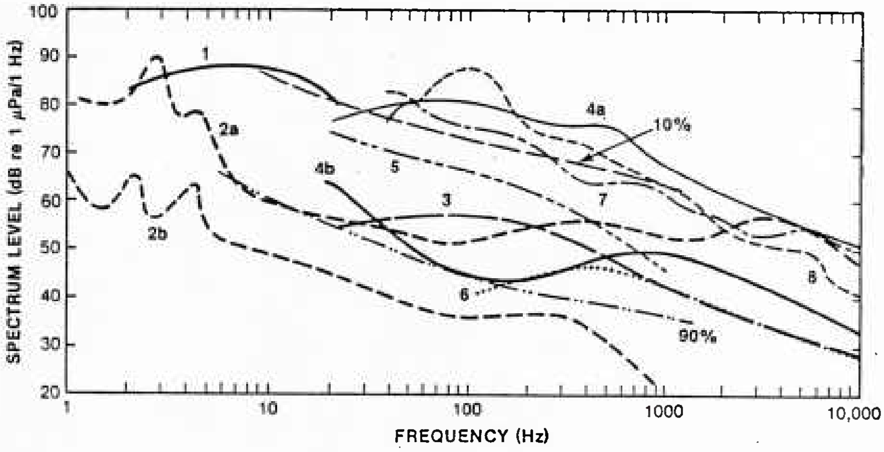


Figure 5.8. Pressure spectra of ice-cracking noise for zero wind speed, recorded during air-cooling periods (JHU/APL, 1982).

the Knudsen curve for sea state zero, have been found under a continuous ice sheet with calm winds and rising temperatures; on the other hand, levels some 40 dB higher have been observed when the ice had been actively cracking under falling air temperatures (Urick, 1983).

A sampling of various published noise spectra under different conditions in the Arctic is given in Figure 5.9, along with curves of levels, were found to be exceeded 10 and 90% of the time by these and other measurements (Urick, 1983).

Noise levels in the marginal ice zone are typically higher than noise levels in the pack ice. Ocean wave/ice interactions such as the flexing, breaking, and collision of floes; turbulence, wave slap, etc., are all potential noise-generating mechanisms in these areas. Diachok (1980) made a series of measurements at a compact ice-water boundary (ice concentration ranged from 1/8 to 7/8 over about 1 km) in the Greenland Sea that shows the spatial variability of noise as a function of distance from the ice-water boundary. Figures 5.10 and 5.11 give a qualitative illustration of the variability of ambient noise near the ice edge. In Figure 5.10, a series of sonobuoy locations across the ice-water boundary is shown schematically, along with local environmental conditions. Figure 5.11 shows samples of representative ambient noise data for those locations. The sea state was approximately 2, and a northeast wind served to maintain the relatively compact ice edge. Figures 5.12 and 5.13 illustrate quantitatively the variations in median ambient noise level that are typical across both a compact and a diffuse ice-water boundary. There is a higher probability of occurrence of diffuse ice-water boundaries than of compact boundaries. Ambient noise levels in the



1. *2-m ice, Barrow Strait, April 1959.*
2. *Old polar ice, Beaufort Sea, April 1961.*
   2a. Noisy periods
   2b. Quiet periods
3. *70% 1- to 1.5-m one-year ice mixed with 30% old floes, September 1961.*
4. *Old polar ice -- shore-fast, Canadian Archipelago, February 1963.*
   4a. Thermal cracking noise present
   4b. Thermal cracking noise not present
5. *Average over two weeks in central Beaufort Sea.*
6. *Deep water open ocean, wind force 0.*
7. *Cape North, 22 February 1971.*
8. *Cape North, 15 March 1971.*
   90% ambient noise level will exceed this level 90% of the time (Urick)
   10% ambient noise level will exceed this level 10% of the time (Urick)

Figure 5.9. Underice ambient noise spectra from Arctic experiments (mostly shallow water) (NUSC, 1983).

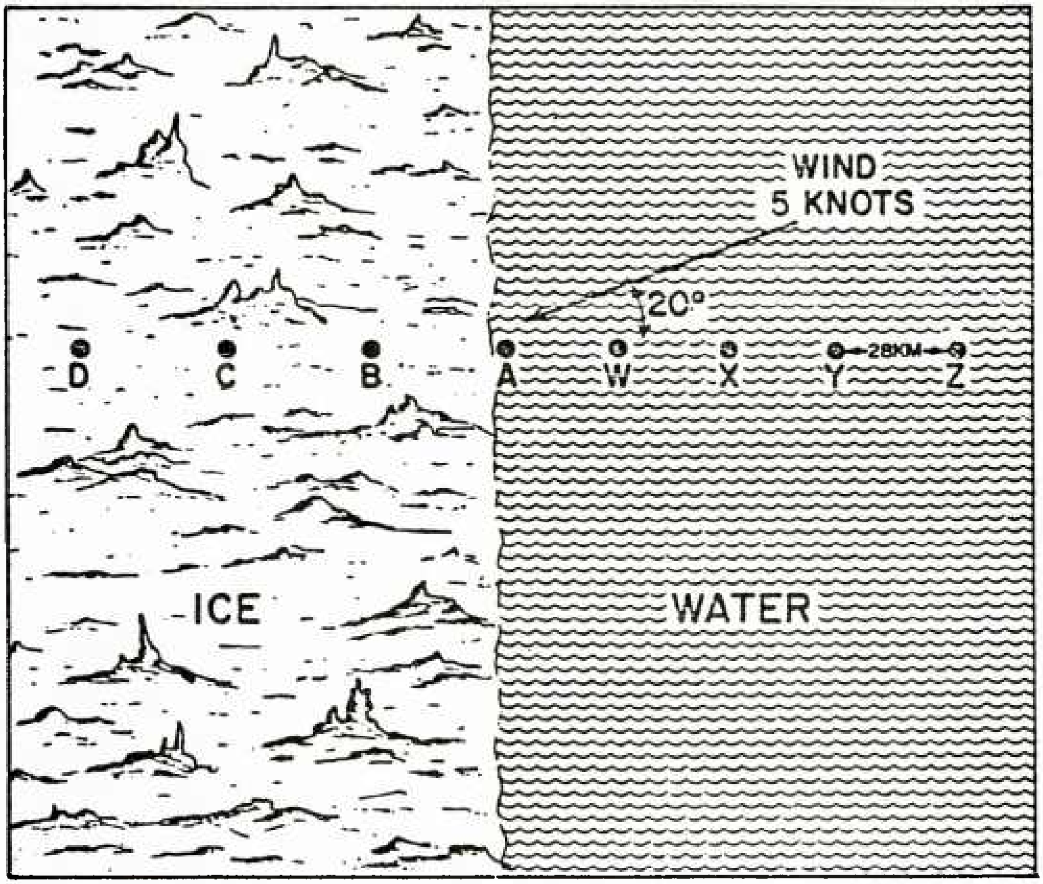


Figure 5.10. Schematic representation of sonobuoy locations and wind conditions relative to the ice/water boundary (JHU/APL, 1982).

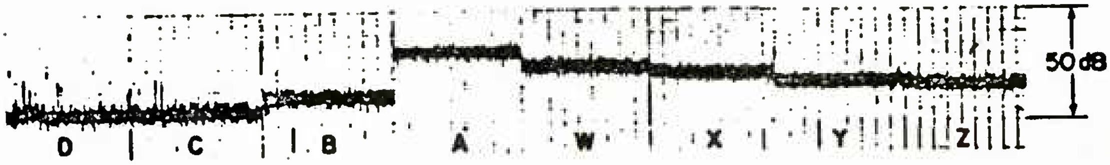


Figure 5.11. Representative strip chart records for 3-min samples of ambient noise data for a one-third octave frequency band at 315 Hz at each measurement site (JHU/APL, 1982).

MIZ also depend on such variables as sea state, water depth, and dominant ocean-wave period. The latter variable is hypothesized as being related to the efficiency of coupling of ocean-wave energy into the ice (Diachok, 1980).

Detectability

As pointed out above, a distinctive feature of the underice environment is a sound-speed profile (Fig. 5.1) that leads to ducted propagation, even at low frequencies. A few recent studies have considered the passive detectability of submarines in a region of ducted acoustic propagation. These studies were concerned with the open-ocean, winter environment in the North Atlantic but provide the basis for possible extrapolation to the Arctic environment. Some experimental data support the general conclusions of the studies (Tyler and Hayeck, 1980; Tyler and Boyles, 1980).

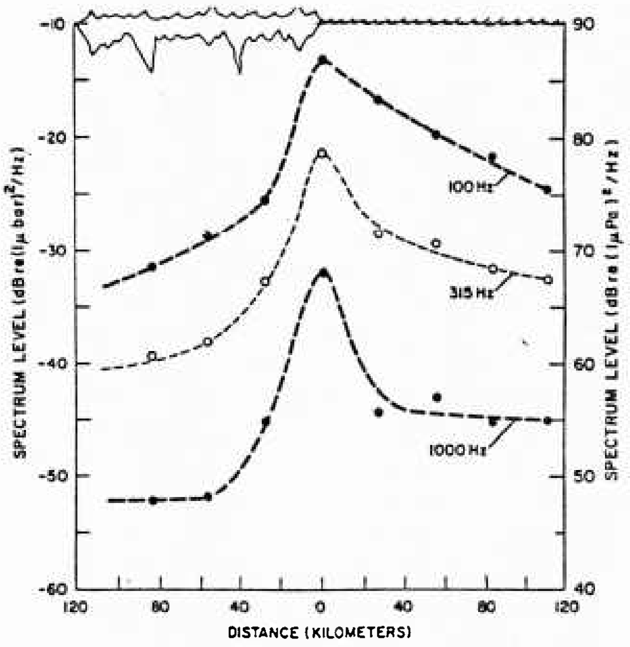


Figure 5.12. Variations of median ambient noise sound pressure spectrum levels with distance from a compact ice edge for frequencies of 100, 315, and 1000 Hz; Sea State 2 (JHU/APL, 1982).

The other determinant of detection range for a given source and sensor system is ambient noise. Figures 5.12 and 5.13 show that ambient noise under the ice pack may be significantly less than in the open ocean, the differences at frequencies of interest being some 8 to 12 dB in the cases shown. In a ducting environment, with nominally cylindrical spreading ($TL \approx 10 \log \gamma$), a decrease in ambient noise of 10 dB corresponds to a tenfold range increase! Although other effects (absorption, energy leakage out of the duct, surface interactions, etc.) will surely prevent realization of this order of range increase, the point is that in a ducting environment, relatively small increases in the figure of merit can lead to significant increases in detection range.

In contrast, ambient noise levels in the MIZ near the ice edge are seen from Figures 5.12 and 5.13 to be significantly (5 to 10 dB) above these of the open ocean, arguing for detection ranges in the MIZ considerably shorter than those cited above.

In summary, we may expect passive detection ranges well under the ice (farther from the ice edge) to be considerably longer than those observed in the open ocean, even in a winter ducting environment, and dramatically longer than those observed in the typical convergence zone environment. On the other hand, an active detection system is subject to scattering from the ice and severe reverberation at tactical frequencies and may offer no prospect of increased echo-detection range. The reverberation environment of an active system at surveillance frequencies will be less severe, but predictions are difficult to make.

Uncertainties

The ice cover forms a complicated boundary for the acoustic propagation channel. Its character varies in areas of moving pack ice, shore-fast pack ice, and the marginal ice zone. Pack ice is generally characterized as having a root-mean-square (rms) roughness of 3 m, with pressure ridge keels to 40 m. The character of the ice (e.g., sound speed, salinity, viscosity, mechanical moduli, and porosity) changes with age, thus complicating acoustic interactions. The effect of the ice cover on acoustic propagation and its role as a unique noise-generating source are key issues in Arctic acoustics. Bottom interactions are of a more usual character. Abyssal plains with deep sediments, ridge areas, and continental shelf and slope regions all exist in the Arctic. Their effects are comparable in importance to those seen in other oceans.

Signal coherence is of major concern in assessing array performance. Water-borne paths dominate the coherence of signal arrivals. Both changes in multipath propagation and ice scattering will reduce coherence to an unknown extent. Bottom-reflected arrivals may also reduce coherence. Bottom-refracted signals are known to arrive coherently, but combining with the overall multipath structure may serve to degrade coherence.

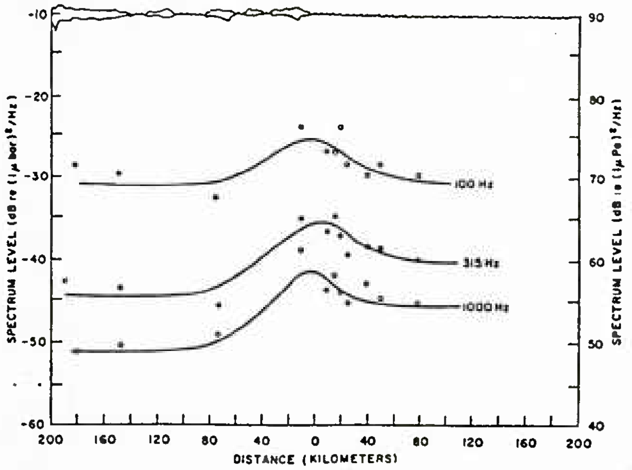


Figure 5.13. Variations of median ambient noise sound pressure spectrum levels with distance from a diffuse ice/water boundary for frequencies of 100, 315, and 1000 Hz; Sea State 1 (JHU/APL, 1982).

Ambient noise in the Arctic is of widely varying character. Knowledge of the time scales involved, and especially the duration of low noise periods, is needed to evalute the potential capabilities of passive acoustic systems in the Arctic region. Numerous ambient noise data bases exist that may well suffice to characterize noise statistics, but their value and the status of ice noise modeling have not been assessed.

Arctic ambient noise can be highly directional in both the horizontal and the vertical planes. Hence, array gains better than the Directivity Index (DI) may be possible. In particular, rejection of local, high-vertical-angle noise sources or localized distant noise sources may exceed the potential for rejection of isotropic noise. Such effects, if present and exploited, would increase detection ranges.

Numerous experiments provide data to define propagation characteristics at low frequencies. However, there is a need to determine the availability of midfrequency (100 Hz to 1 kHz) propagation data coupled with appropriate environmental, surface, and bottom characterizations.

It is conjectured that scattering of signals at frequencies above about 50 Hz from the underside of the ice surface is an important loss mechanism. The ice roughness and ice ridging play a role. This scattering loss is not well understood and data are conflicting. The ice, perceived as a plate, also plays a role in propagation. Horizontal and vertical component seismometers attached to the ice plate are regularly and effectively used as acoustic detectors (Lyon and Boyle, 1962); they could potentially play a role in a detection scenario that exploits acoustic propagation through the ice cover. The effect of such a possibility on submarine detection and classification is unclear.

Concluding observations

In the previous comments, passive surveillance systems (long towed or emplaced arrays) and passive tactical systems were considered. Just as scattering from the ice impedes propagation, it also produces a highly reverberant environment. Thus, surface reverberation in Arctic waters could be a more severe problem for an active system than would open-ocean surface reverberation. Doppler discrimination against surface reverberation might prove to be an effective technique, but the level and the spatial spread of the surface return remain unknown. Reverberation is thus a major concern for any active system that might operate in the Arctic Ocean. A rich data base from explosive sources is available, but appreciably less vertical and horizontal directionality information exists. In addition, supporting characterizations of the rough scattering surface are needed.

Bottom reverberation is also important at all ranges. Reverberant returns from basin boundaries at very long ranges (to 2500 km) have been observed after explosive shots in the Arctic Ocean (Buck, 1974).

Active acoustic performance factors in MIZs are less easily characterized. Here, partial ice coverage and ice motion radically change the effect of the ice on scattering loss, propagation, and reverberation. Furthermore, these regions often occur at the juncture of different water masses, and sound-speed profiles can be complex.

Ice detection and avoidance may necessitate the use of forward- and upward-looking, high-frequency, active sonars. The detectability of such sonars is not known, but tight echo-return beams on upward-looking sonars would be extremely difficult to maintain due to the effects of ice scatter. Unless kept to very low levels, acoustic energy could be scattered into angles that would propagate to significant ranges. Forward-looking beams, of course, heighten the likelihood of signal propagation to long ranges. This behavior is somewhat mitigated by losses upon reflection from the ice surface, but the extent of this loss is unclear, especially at very high frequencies.

The excellent propagation conditions (especially at frequencies below 50 Hz), the prevalence of low ice-noise levels, and the lack of shipping noise all suggest that the passive detectability of submarines would be greater in Arctic waters than in current patrol areas. The significance of this conclusion is greatest relative to the concept of fixed systems. Any increased detectability by a tactical (submarine-borne) sonar system arising from improved propagation and lowered ambient noise must ultimately be evaluated in terms of the correspondingly increased detection range presumably available to an adversary, an issue of ''acoustics advantage'' currently favoring the quieter U.S. submarines.

References

Anti-Submarine Warfare Systems Project Office (1977). *ASW Sensors in the Arctic.* ASWR-77-116, September.

Brown, J. R. (1964). Reverberation Under Arctic Ice. *J. Acoust. Soc. Am.*, v. 36, p. 601.

Bradley, D. C. (1973). *Long Range Acoustic Transmission Loss in the Marginal Ice Zone North of Iceland.* U.S. Naval Ordnance Lab Rept. 72-217.

Buck, B. M. (1968). Arctic Acoustic Transmission Loss and Ambient Noise. In *Arctic Drifting Ice Stations*, J. E. Sater (ed.), Arctic Institute of North America.

Buck, B. M. (1974). Arctic Environmental Low Frequency Acoustics Measurements, Models, and Plans. *International Workshop on Low-Frequency Propagation and Noise 2*, Woods Hole, Massachusetts, 14–19 October.

Diachok, Orest (1980). Arctic Hydroacoustics. *Cold Regions and Science Technology*, v. 2, pp. 185–201.

Johns Hopkins University/Applied Physics Laboratory (1982). *A Perspective of Submarine Arctic Operations (U).* DRC No. Y-K-949-101, March. SECRET.

Lyon, W. K. (1959). *The Polar Submarine and Navigation of the Arctic Ocean.* U.S. Naval Electronics Lab, San Diego, California, Research Report 88 (Reissued 21 May 1959).

Lyon, W. K. and R. Boyle (1962). The Arctic Ocean. *Undersea Technology*, v. 3, pp. 17–20.

Mellen, R. H. and H. W. Marsh (1963). Underwater Sound Reverberation in the Arctic Ocean. *J. Acoust. Soc. Am.*, v. 35, pp. 1645–1648.

Milne, A. R. (1964). Underwater Backscattering Strengths of Arctic Pack Ice. *J. Acoust. Soc. Am.*, v. 36, p. 1551.

Naval Arctic Manual (1970). U.S. Naval Oceanographic Office, NSTL, Mississippi, ATP 17 COMTAC Publication.

Naval Underwater Systems Center (1983). *Consolidated Arctic Warfare Handbook (U).* (Preliminary review copy), 30 September. SECRET

Orr, G. H. (1975). *Arctic Submarine ASW (U).* Masters Thesis, Naval Postgraduate School, Monterey, California, March. SECRET

Pedersen, M. A. (1983). Key Arctic Propagation Topics. Prepared for presentation to the Naval Ocean Research and Development Activity, May.

Tyler, G. D. and C. S. Hayeck (1980). *Preliminary Analysis of Detectability (U).* JHU/APL STA-80-010, March. SECRET

Tyler, G. S. and C. A. Boyles (1980). *Briefing on the Detectability (U).* JHU/APL STA-80-002, February. SECRET

Urick, Robert J. (1983). *Principles of Underwater Sound.* McGraw-Hill, Inc., p. 423.

Welsh, J. P. and N. J. Reshew (1985). *Proceedings of the Arctic Oceanography Conference and Workshop*, June 11–14, Naval Ocean Research and Development Activity and Commander, Naval Oceanography Command, NSTL, Mississippi.

6. Submarines in the Arctic

Introduction

In August 1958, the nuclear-powered submarine, USS NAUTILUS, under the command of Capt. W. R. Anderson, crossed the Arctic Ocean in 96 hours using the open sea that lies beneath the ice (Lyon, 1963). In March 1959, the USS SKATE demonstrated under difficult winter conditions that surfacings through the ice could be made through frozen openings in the ice or ''skylights.'' She was able to break her way through to the surface on 10 separate occasions during this 3090 nm polar cruise (Wittmann, 1959). In further demonstration of the capability of submarines to sail the Arctic Ocean, the USS SKATE departed from New London, Connecticut, and the USS SEADRAGON departed from Pearl Harbor, Hawaii; both proceeded to the Arctic Ocean, and on 31 July 1962, met each other at a prearranged point and time beneath the sea ice (Lyon, 1963).

With the advent of nuclear underice submarine operations in the late 1950s, demands for sea ice intelligence and prediction services deviated somewhat from past requirements for surface operations in ice-covered seas. Moreover, in recent years, the need for sea ice knowledge has accelerated correspondingly with increased submarine underice activities and ASW surveillance programs.

Knowledge concerning the outer limits of the ice pack continues to hold importance. Ice concentration, i.e., the percent of ice cover in relation to the overall ice-water coverage, remains important. The submariner needs to know the relative distribution of ice and water, the nature and size of the ice forms that are present, and the size of the open water areas (and if ice clutter exists in these areas). Knowledge of ice thickness distribution, particularly during the Arctic winter (late September to early June) when there may be a dearth of open water areas, is needed to support planning and operations of underice exercises to enhance the capability for tactical operations. The frequency and distribution, by size, of ridge keels are of paramount importance to the submarine operator because of their impact on underice navigation, particularly in shallow waters, and their effects on submarine and weapons and sonar systems.

Wittmann (1959) considered underice submarine navigational techniques according to four operational conditions: sustained surface operations near ice, surface operations within ice, underice-periodic surfacings, and sustained submerged operations. Some of Wittmann's comments and ideas, which are still useful today, are summarized.

- Sustained Surface Operations Near the Ice

A primary problem in approaching sea ice boundaries from the open ocean may be the danger of collision with icebergs and ice floes. Predictions of ice distribution and basic information and familiarity with ice conditions will be helpful. Some knowledge of the sciences of oceanography and meteorology will also be helpful to the submarine navigator in the Arctic.

Specifically, the navigator approaching an ice boundary should be aware that the ice he is approaching is probably moving through the combined effects of currents and winds. Currents may be approximated from appropriate charts. The wind drift of the ice may be approximated from surface weather isobaric charts and from one's own surface observation by applying the following somewhat simplified rules. Ice drift direction is along the isobars or approximately 30° to the right of the surface wind (clockwise around high pressure, counterclockwise around low pressure). Ice drifts at a rate of approximately 1/50 of the wind speed.

Another useful (empirical) rule concerns the fact that small masses of sea ice are brought into equilibrium by the wind stress more quickly than large masses. With brisk offshore winds, small sea ice floes tend to outrun the larger ones. As a result the appearance of isolated ice fragments indicates gradually increasing concentrations, large floes, and an indistinct, widely dispersed boundary ahead. On the other hand, a period of sustained onshore winds portends a definite boundary of heavily concentrated ice ahead. When accompanied by clear weather, sharp ice boundaries may at times serve as excellent navigational aids.

- Surface Operations Within Ice

When operating on the surface within the boundaries, light winds or calm conditions are most favorable. Slight negative buoyancy astern to keep the propellers somewhat protected is advisable. As with surface ships, backing in ice is dangerous, especially with twin-screw ships. Watch the odd pieces that frequently break and drift alongside and, again, astern. This condition is likely to occur frequently if near the boundary and when swell is present. Avoid hummocked or ridged floes and glacial fragments (bergs, bergy bits, growlers) embedded in the ice. Working into the ice at periscope depth is, of course, never recommended.

- Underice-Periodic Surfacings

In submerged submarine operations with daily or periodic surfacings, knowledge of the behavior of the Arctic ice cover is probably most important. Once well within the Arctic pack ice boundaries, the submarine navigator's interest in sea ice features narrows in scope. Two primary features become important. The first is the underwater protuberances or the keels of the pressure ridges; the second is the openings in the ice (leads or polynyas).

Underwater protuberances form primarily from convergent movement within the ice; to a lesser extent they may be caused by stresses created by thermal gradients. The latter cause is easily comprehended when one considers that the surface of a 3- to 4-m thick floe of multiyear ice in midwinter approaches the air temperature of -35° to -40°C. The underside of this relatively thin layer is at -1.5°C. Buckling, such as frost-heaving, naturally occurs. More important, however, in causing the ridges and their underwater counterparts is the deformation resulting from convergent wind stress. As floes of ice press together, hummocks arise in the sea ice, a nonhomogeneous substance composed mainly of ice, water, salt crystals, brine, air bubbles, and marine plankton.

Early basic knowledge concerning pressure ridge keels has come to us indirectly from manned ice floe stations and from the experience of ships frozen in the ice (JEANNETTE, FRAM, SEDOV). Surface hummocks and ridges (lines of hummocks) observed by these stations and vessels were multiplied by three or four to obtain an estimate of their draft. Numerous submarine observations of the bottom-side of the sea ice cover have provided more accurate data. General expectations are that ridge keels in the sea ice of the central Arctic Ocean will not exceed 40 m.

From considerations of divergence in the field of wind stress (as computed from isobaric charts), one would expect rarefaction or spreading. Since ice is not homogeneous, this spreading results in the development of cracks and irregular openings. Such openings are indeed found when ice moves away from coastlines.

The openings that form in the Arctic ice cover are not stable, especially in midwinter. At temperatures of -40°C they tend to freeze at a rate of more than 8 cm per day. Also, the openings within the ice cover may close rapidly, since changes in the isobaric structure create changes in the field of wind stress.

It is quite conceivable that in the near future the Arctic submarine navigator may utilize real-time sea ice data from satellites to arrive precisely at predetermined openings in the ice cover.

- Sustained Submerged Operations

During sustained submerged submarine operations under Arctic pack ice, inertial guidance navigation and as thorough an understanding as possible of the bathymetry are most important. Initially, it would seem that the only means by which ice affects such navigation is in predicting the ice bottom features and lead characteristics as the submarine approaches the Arctic pack; in providing assurance that ice pinnacles will not exceed cruising depth; and predicting the position of the ice-water boundary at the end of the patrol. Several ice and related environmental characteristics may be added in the future to improve the ability of the navigator to position himself in emergency cases where existing navigational systems might fail. Present ice detection equipment enables the navigator to continually approximate such sea ice features as thickness and roughness, features that characterize certain wide portions of the Arctic. Also, the depth and temperature salinity characteristics of various Arctic water masses enable the navigator to approximate the region of the Arctic basin in which he is operating.

These examples show that ice and oceanographic features are becoming better known with each additional polar patrol of our nuclear submarines and with each additional year's data provided by scientists from other observational platforms. For these reasons, the demonstrated potential of the underice submarine is invaluable for an oceanographic and ice data collection platform. This should be of interest to prospective polar navigators. The polar navigator, in turn, should have a strong self-interest to obtain data for the oceanographic and hydrographic disciplines, for the ultimate usefulness of data is closely related to the ability to accurately fix the position in space.

Oceanographic measurement capabilities with the SSN 637 class submarine

Underice submarine cruises in the Arctic offer the unique opportunity to collect data otherwise unobtainable and, in some cases, in areas generally inaccessible by other means. The range of environmental measurements required to support Arctic submarine programs include seasonal determinations of acoustic transmission, fluctuation and ice scattering, ambient noise characterization, and the requisite environmental characterization (ice profile statistics, water column properties, and bottom characteristics).

To satisfy these generalized requirements the following environmental parameters need to be measured.

- Temperature
- Salinity
- Sound velocity
- Current
- Water optical quality

- Underice surface characteristics (i.e., ice roughness, ice thickness, acoustical and physical ice properties, incidence and size of icebergs and keels)
- Seafloor characteristics (i.e. bottom profiling, acoustical and geophysical properties of the bottom)
- Ambient Noise

Experimental programs will require simultaneous system and environmental support measurements to establish the relationships between the various environmental factors and equipment performance.

References

Lyon, Waldo (1963). The Submarine and the Arctic Ocean. *The Polar Record*, v. 11, n. 75, pp. 699-705.

Naval Arctic Manual (1970). U. S. Naval Oceanographic Office, NSTL, Mississippi, ATP 17(A), COMTAC Publication, January.

Wittmann, W. I. (1959). Ice and Subsurface Navigation. *Navigation*, v. 6, n. 7, Fall.

7. Arctic remote sensing

Introduction

The inaccessibility and severity of the Arctic regions and the high cost of logistic operations precludes the practical use of surface platforms (i.e. ships, ice stations) to make synoptic or local observations on a large scale. Satellite and aircraft platforms equipped with remote sensors can be used to make repeated broad area and local oceanographic and sea ice observations. Buoys designed to measure atmospheric, oceanographic, and acoustic phenomena over extended periods can be air-dropped or emplaced through aircraft landings on the ice cover.

Visual systems

The LANDSAT satellite uses a multispectral scanning system with four frequency bands. It has a resolution of 60–80 m and ground coverage of 185 x 185 km. In the polar regions, coverage of a given location (up to 81°N) is repetitive for 2–5 days followed by a 13- to 16-day gap. Data can be obtained only when the satellite is within line of sight of a receiving system. Limitations include no imagery during periods of cloud cover and darkness, and imagery cannot be collected at regular short intervals (2 days or less). The imagery is useful for describing ice conditions and tracking the drifting ice floes in small localities. Figure 7.1 shows a LANDSAT visual image taken over east Baffin Bay in April 1979. The smallest floes are discernible, but ridges and hummocks cannot be seen.

The NOAA satellite provides visual imagery utilizing a VHRR. Each swath is 2350 km wide and a location is imaged every day. There are no latitude restrictions on coverage as the orbit is near polar. Surface resolution is only 800 m at nadir, so many important ice features may be lost. The system is restricted by darkness and cloud cover. The NOAA VHRR is useful for monitoring the large-scale extent and behavior of the ice cover. Figure 7.2 shows a visual image taken with the NOAA-4 VHRR over the Bering Sea on 25 March 1976. Sequences of these images can be used to monitor the changing structure as well as the movement of features in the pack ice. The ice structure changes and movements reflect variations in the large-scale, low-level wind flow patterns. The wide open water or thinly frozen offshore areas seen in this

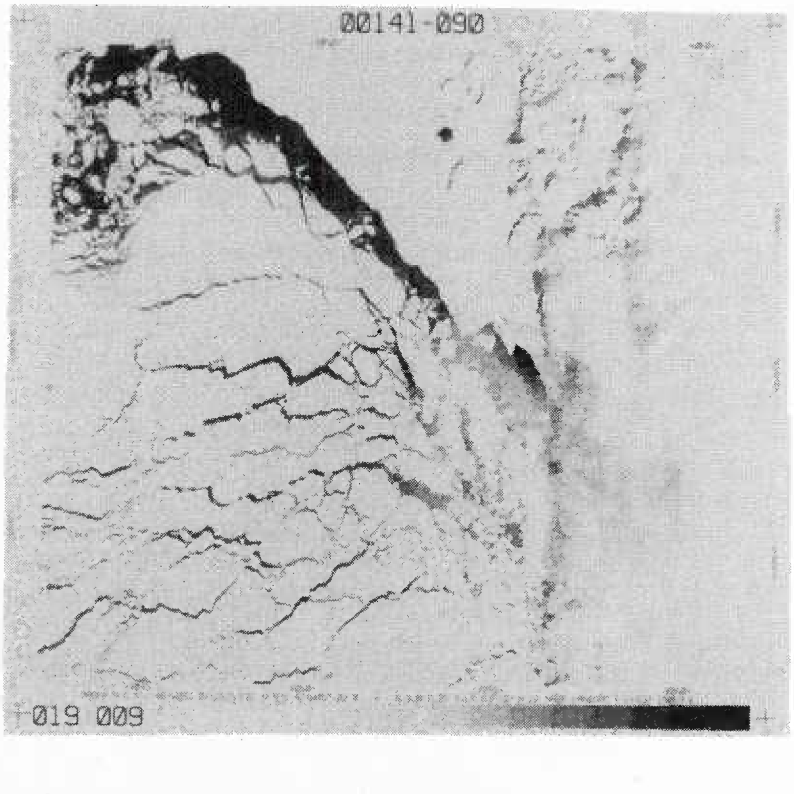


Figure 7.1. LANDSAT visual image taken over east Baffin Bay—West Greenland in April 1979. Recent fractures pass through first-year ice floes of many sizes. Darker-toned ice is thin new ice with no snow cover. Ice ridges are indiscernible.

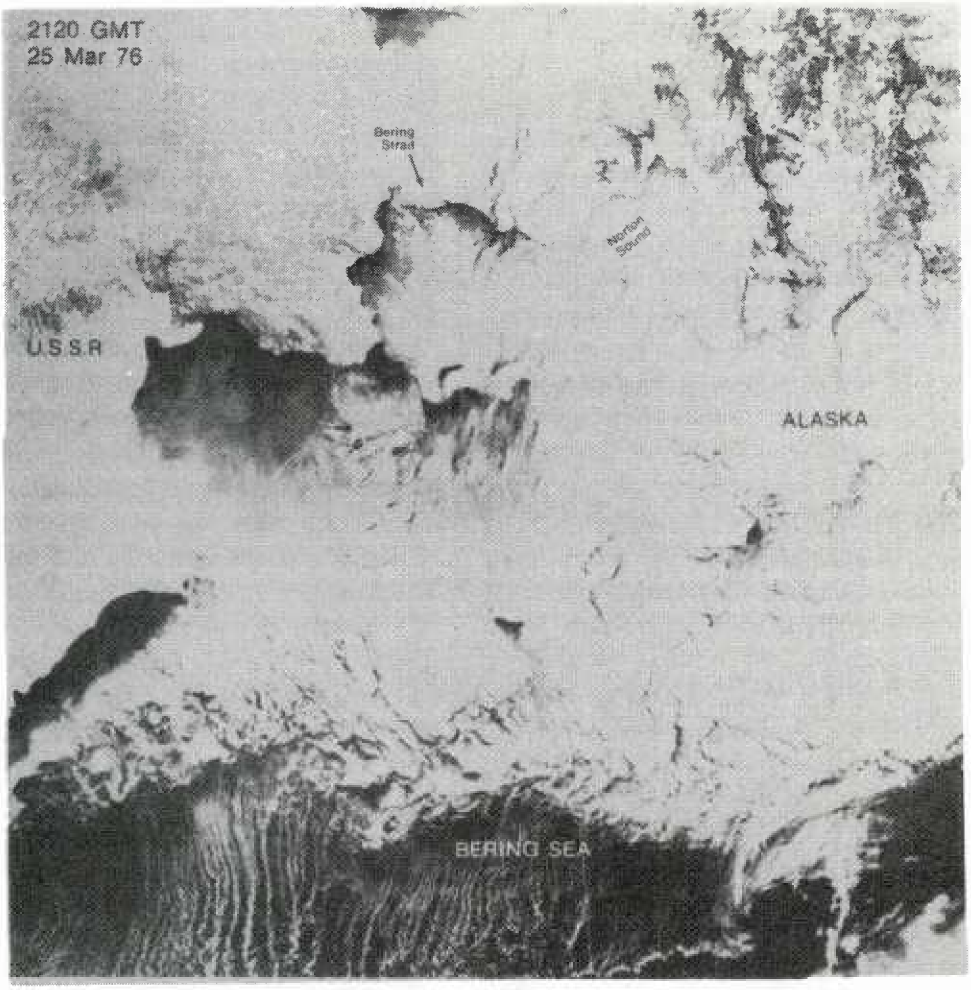


Figure 7.2. NOAA VHRR visual image taken over the Bering Sea on 25 March 1976. Image sequences are used to monitor changing ice structure and movement, which reflect variations in wind flow patterns. Open water on thinly frozen offshore areas suggest a recent northwesterly wind that has caused development of a very diffuse ice edge at the outer limits of the ice field.

image suggest a recent northwesterly wind flow. These offshore winds have caused the development of a very diffuse ice edge at the outer limits of the pack ice field.

The Defense Meteorological Satellite Program (DMSP) satellite employs a very high resolution visual system that has a swath width of 2900 km. This imager has a surface resolution of 600 m at nadir. DMSP provides repeated coverage when two satellites are used simultaneously. As with all visual systems, darkness and cloud cover are its primary limitations. Figure 7.3 shows a DMSP visual image taken over the Sea of Okhotsk on 13 April 1972. Many individually distinct ice floes are seen in the open pack ice east of Sakhalin Island. The heaviest ice concentration occurs in the northern portion of the sea. Offshore polynyas are clearly visible along the U.S.S.R. coast.

Thermal infrared systems

Thermal infrared (TIR) systems sense the temperature of the upper snow or ice surface. Thin ice areas show up warmer than thicker ice, which makes it possible to delineate these areas during the early stages of ice development. However, variations in ice surface temperatures after the ice becomes thicker than 1 m are small and readily obscured by variations in the thickness of the snow cover. Consequently, TIR cannot be used to separate the thickest first-year ice from multiyear ice later in the growing season. Additionally, TIR imagery is obscured by clouds that can be warmer or colder than sea ice. The advantage of TIR imagery, apart from the fact that it gives a view very different from visual imagery, is that it is not limited by darkness.

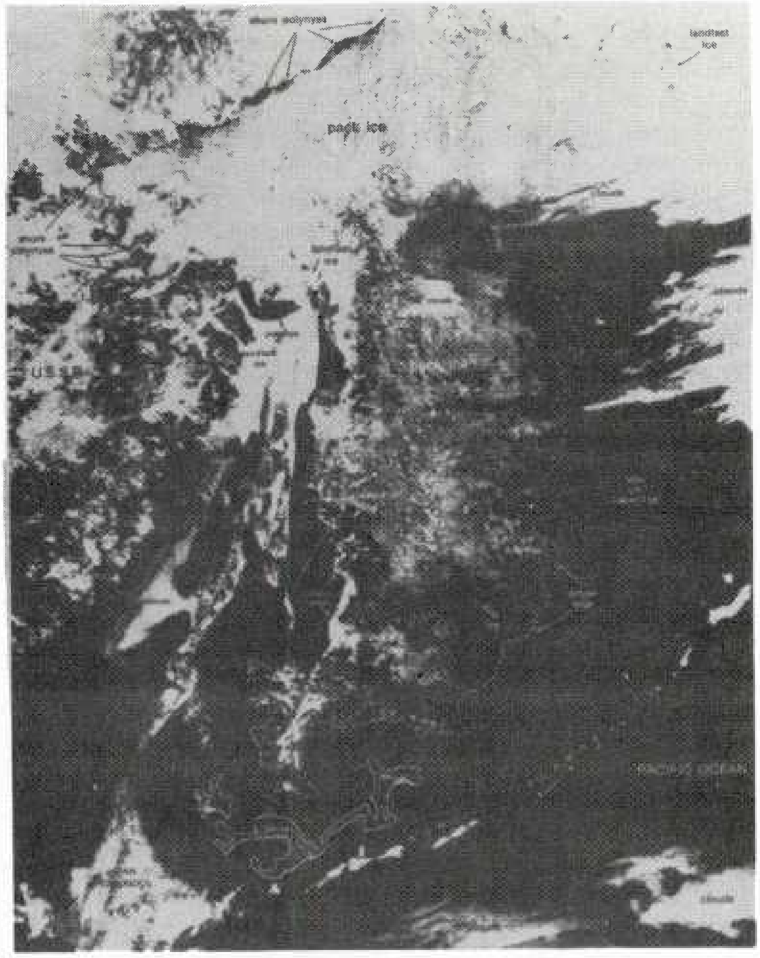


Figure 7.3. DMSP visual image taken over the Sea of Okhotsk on 13 April 1972. Distinct ice floes are easily discernible in the ice pack east of Sakhalin Island. Offshore polynyas are clearly visible along the U.S.S.R. coast.

The most useful TIR system in orbit is the VHRR-TIR onboard the NOAA satellite series. The swath width, resolution, and repeat interval are the same as for the NOAA-VHRR visual imagery. The TIR imagery can be used for large-scale studies of ice extent and movement. Figure 7.4 shows a TIR image of sea ice taken over the Beaufort Sea.

Passive microwave systems

Passive microwave systems are not affected by clouds or darkness. The major problems with these systems are lower resolution and the need for more experienced interpreters.

The NIMBUS-5 Electrically Scanning Microwave Radiometer (ESMR) and the NIMBUS-7 Scanning Multifrequency Microwave Radiometer (SMMR) have footprints (the size on the ground of each picture element or pixel) of approximately 25 km. Within each footprint there might be several types of sea ice, plus open water. Therefore, the passive microwave signature for each pixel will be the average of the signatures (the so-called brightness temperatures) of the different elements within the footprint. Because of the great difference in brightness temperatures of sea ice and open water, these elements are easily differentiated by the ESMR and other passive microwave systems. Consequently, satellite-borne passive microwave systems have been very effective in mapping the variations in the large-scale extent of sea ice.

Active microwave systems

The synthetic aperture radar (SAR) system has been the most promising of the several different active microwave systems used in the study of sea ice.

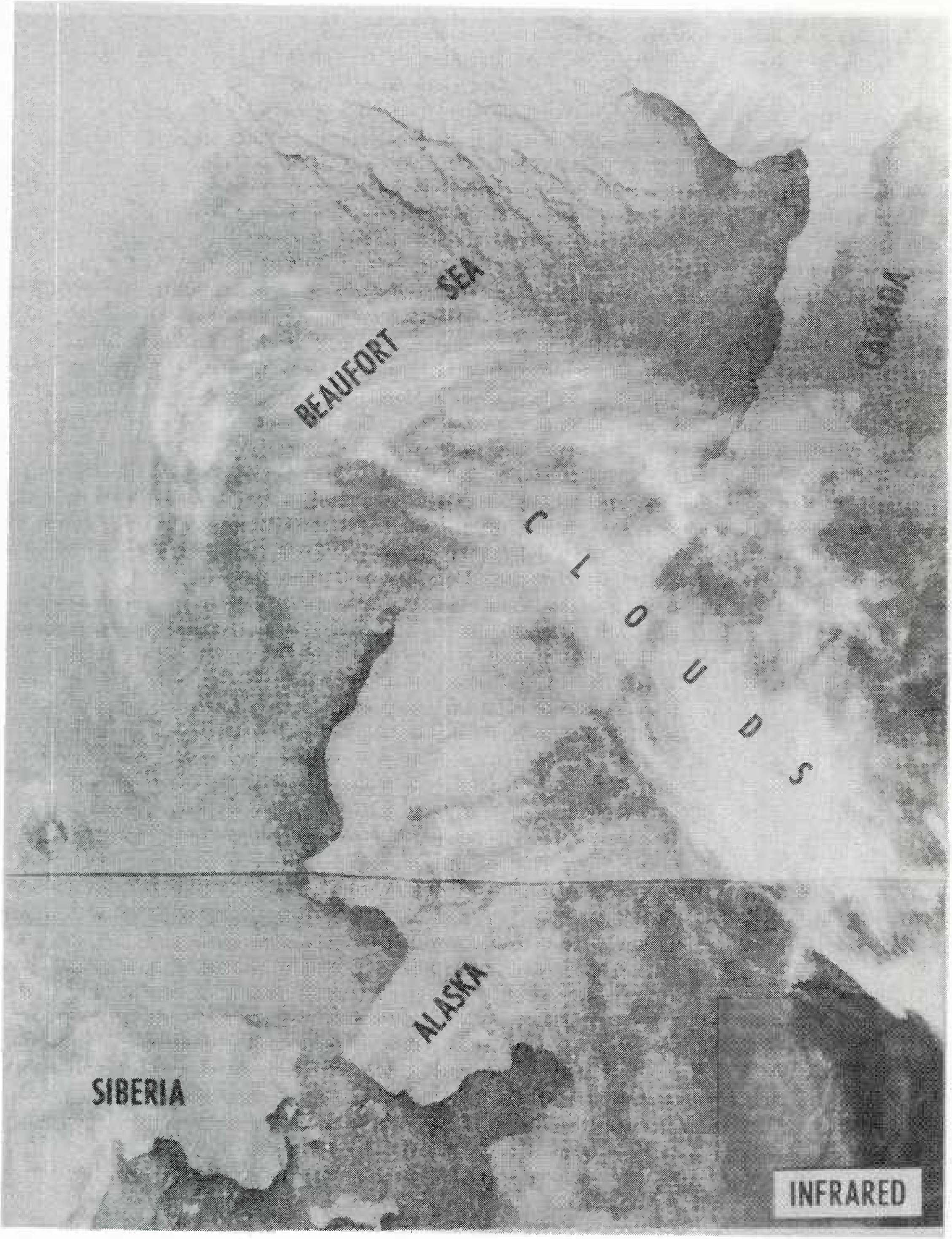


Figure 7.4. NOAA TIR sea ice image taken over the Beaufort Sea north of Alaska and Canada. The negative photographic print used here depicts ice-free or thinly ice-covered fractures (dark gray lineations) oriented north-south in the colder (light gray) sea ice cover. High clouds appear colder and low clouds appear warmer than the sea ice. Thinly ice-covered offshore leads (dark toned) are present along the Alaskan and Canadian coasts. Sequential TIR imagery can be used to study large-scale ice dynamics.

The L-band (wavelength of 25 cm) SAR system on SEASAT has been the only deployment to date. The data from this satellite, which failed after 3.5 months, demonstrated both the power and the problems of SAR. The system imaged a 100-km swath 20.5° off nadir at a resolution of 25 m on the ground. Many sea ice/water features in the pack ice, such as floes, leads, and ridges, were distinctive on the SAR imagery and these features could be reidentified over periods of weeks. This capability can be coupled with the fact that the position of imagery pixels can be located with an accuracy of 250 m (if land points occur in the imagery, the error is less than 100 m). Figure 7.5 shows SEASAT SAR imagery taken off the northwest coast of Banks Island, Canada, on 3 October 1978. Open water or thin ice-covered fractures in the ice field are easily identified by their low radar returns and angular shapes, along with the knowledge (based on earlier imagery) that the fractures are recent.

Thicker, first-year ice-covered fractures would look similar at L-band frequencies, but through the analysis of sequential imagery over a growth season, the interpreter would be able to accurately assess the age, thus thickness, of ice-covered fractures. Ridges and areas of ice rubble are easily identified on this imagery. These areas give high radar returns and are concentrated between the smoother (lower radar return), somewhat rounded, multiyear ice floes. Note that the intensity of ice roughness in an area is strongly related to the size of the multiyear ice floes. Many small, rounded, multiyear ice floes indicated past intense deformational activity, thus, more hummocks and ridges. Ketchum (1982) discusses the interpretation of SEASAT SAR imagery during the summer and fall seasons.

An all-weather, all-light conditions SAR capability, such as that shown in Figure 7.5, is needed for near real-time ice forecasts and inputs to ice models. This capability could

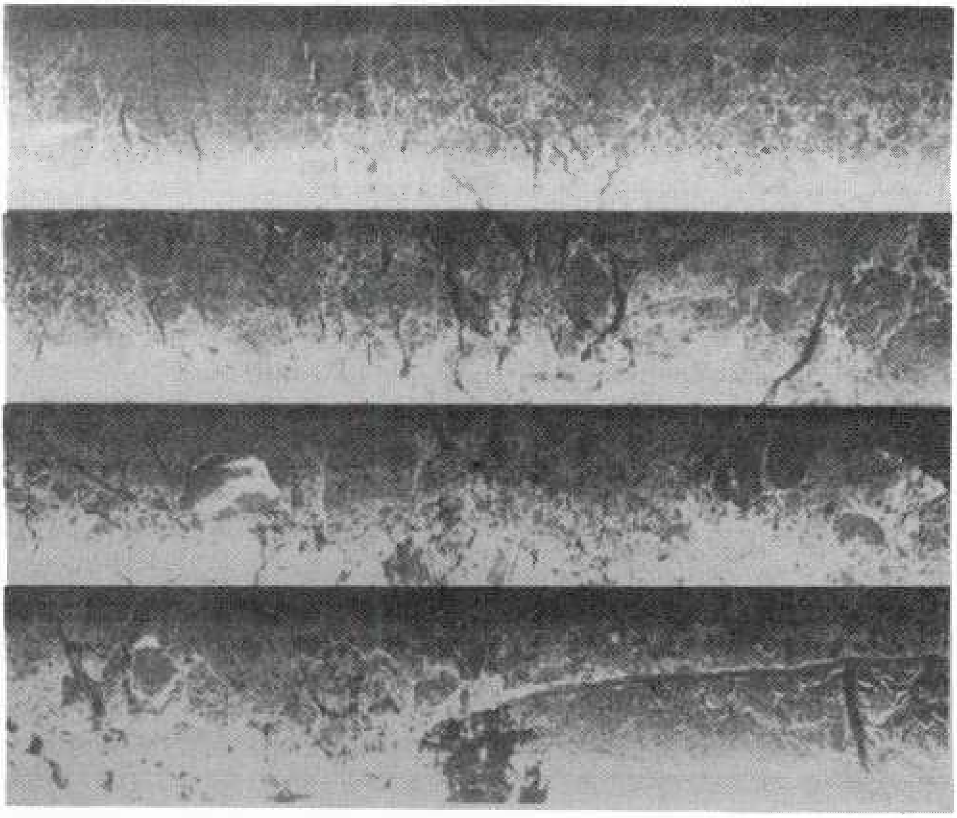


Figure 7.5. SEASAT SAR imagery of sea ice in the Beaufort Sea off the northwest corner of Banks Island, N.W.T., on 3 October 1978. The 100-km wide, high-resolution image clearly shows the distribution of open water/thin ice-covered fractures (dark-toned angular features) and the ridges and rubble zones (light toned) lying among the multiyear ice floes. Note that the smaller rounded floes are strongly associated with a higher degree of apparent ice deformation. Ice island, T-3, is present in the western portion of the scene.

also be used in operational scenarios requiring broad scale, real-time surveillance to provide guidance for other platforms in tactical operations. For example, this sort of ice information, if transmitted to a submarine operating under the ice, would be invaluable in making decisions concerning operational maneuvers. Or, aircraft deployments for delivery of air-droppable systems could be guided by the ice information provided by a satellite SAR system. The uses of SAR seem unlimited for operational support, as well as for ice research. The SAR clearly has great potential in studying the drift and deformation of pack ice, as well as for identifying and positioning important sea ice features. The major problems with the SEASAT SAR were that data processing was extremely slow and that observations could be made only when line-of-sight data transmissions were possible due to the extremely high data rates. Also, at L-band frequencies, first-year ice could not be distinguished from multiyear ice based on backscatter differences.

Much more rapid processing should be possible with turnaround times of 3–6 hours. In fact, it is also possible to transmit degraded real-aperture images in real time to operational sites, such as ships transiting pack ice or operating along the ice edge. It should also be possible to obtain a much wider image swath (200–300 km), which would greatly improve coverage. Finally, by going to higher frequencies (C or X band, 2.5- to 7.5-cm wavelengths) discrimination between first-year ice and multiyear ice would be improved.

There are two other types of active microwave systems—radar altimetry and scatterometry. A radar altimeter (deployed on GEOS-3 and SEASAT) is a nadir-viewing instrument that measures the height of the satellite above the ice surface with the precision of a few centimeters. In present systems, it has a footprint of 2 x 7 km. Because of the great difference in returns from sea ice and open water, altimetry data can be used to fix the ice edge locations to within a few kilometers. Altimetry data can also be correlated with mathematical models to specify the ice roughness. One problem is that the return from undeformed ice is so large that the additional contribution as a result of ridging is very small. Radar altimeters also measure sea state and wind speed in the open ocean.

A scatterometer is a calibrated, downward-looking radar that measures the backscatter coefficient of the underlying surface. It can also be used to determine sea ice boundaries and surface roughness. Scatterometry can be used to discriminate between first-year ice and multiyear ice, as well as to estimate surface wind velocities over the open water based on measured sea state. In SEASAT, the scatterometer measured backscatter over a 1500-km swath with a resolution of 50 km.

Airborne remote sensing measurements

Infrared line scanners: These systems provide good resolution images of the surface temperature distribution. The swath width of these systems, which commonly have a 120° scan angle, is a function of aircraft altitude. The capability to obtain high-quality imagery during darkness is a primary advantage of the IR line scanner; however, underlying clouds preclude data collection. Many important sea ice parameters can be detected and identified using IR line scanners because of the combination of good system surface resolution and the high thermal contrast of the sea ice features. IR line scanners can be used to map ice edges, concentrations, water openings, pressure ridges, and relative ice thicknesses during the early stages of ice development. After the ice reaches a thickness of about 1 m, variations in surface snow cover make thickness discrimination more difficult. Figure 7.6 shows a section of IR line scanner imagery taken in the Arctic Basin during daytime in May. Areas of open water and thin ice cover appear much warmer (lighter tones) than the thicker, more heavily snow-covered, multiyear ice floes. Ice pressure ridges and hummocks are well portrayed. Solar heating and shadows enhance the thermal contrast of the ridges and hummocks.

Laser surface profiler: The laser system used in the sea ice community for sea ice roughness studies over the past years employs the Spectra-Physics Geodolite 3A. This unit uses a modulated CW laser technique to obtain continuous measurement of the instrument height above the surface. The illuminated spot on the surface from a height of 304 m is only 3 cm in diameter. When measuring the height of sea ice pressure ridges, errors of 10% or less can be expected. The continuous ice surface profile provided by the laser can be computer analyzed to determine the frequency distribution of ice pressure ridges by height. A reflectometer coupled with the laser system can be used to provide useful complementary data by depicting surface reflectivity of the sunlight and the transmitted laser light. This information enables distinctions of low reflective areas of open water and dark new ice types from highly reflective areas of the thicker snow-covered ice along the two-dimensional profile. Using this data, statistical estimates of ice concentrations and the distribution of open water areas can be made (Radl and Welsh, 1983). Aircraft altitudes of less than 1500 m are usually necessary when using this system because of the low power output (25–40 mW). The laser system is effective under any light

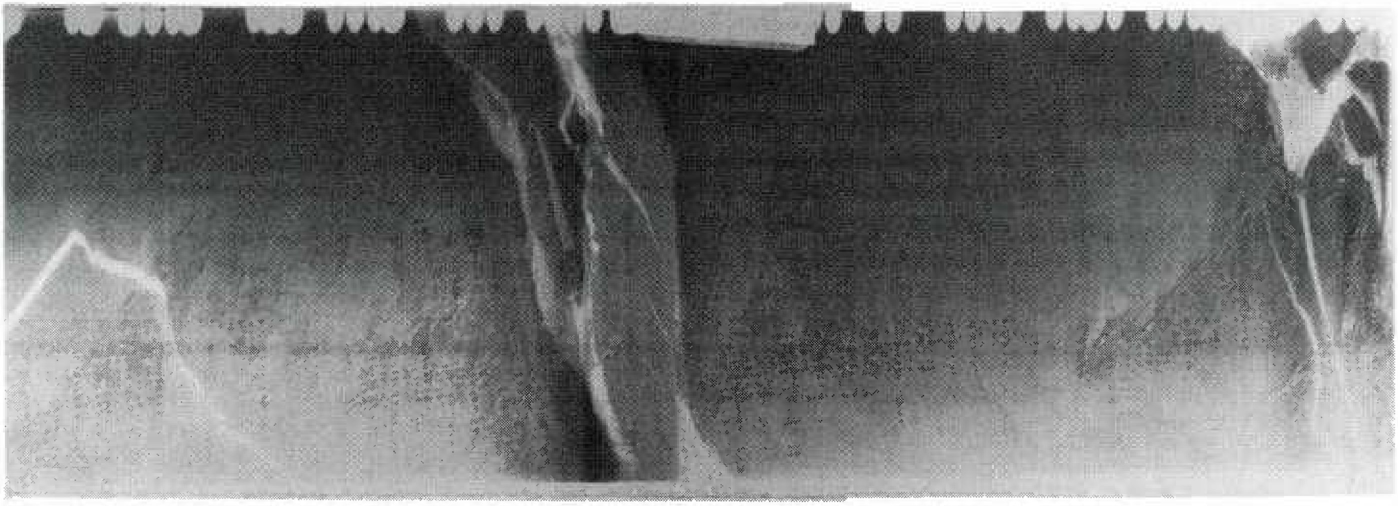


Figure 7.6. Infrared line scanner imagery from the Arctic Basin during daytime in May. Warmer (lighter tones) open water/thin ice-covered fractures are sharply contrasted against thicker first-year ice and thick, snow-covered multiyear ice. Solar heating and shadows enhance thermal contrast of ridges and hummocks.

conditions, but clouds beneath the aircraft will prevent data collection. Examples of laser and reflectometer profiles of sea ice and water are shown in Figure 7.7. Aircraft altitude variations have not been removed from the laser profile example but can be easily accomplished using a 3-step filtering technique.

Passive Microwave Imagers: Airborne passive microwave systems have become more popular in Arctic research in recent years for two primary reasons. First is an increasing realization that sensors capable of observing sea ice during all weather and all light conditions are essential for supporting ice forecasting and other operational needs. Second, advancing technology has permitted improved system performance (namely, surface resolution and dynamic range). With the improved surface resolution, it is now possible to image signatures of small discrete features and areas, thus enabling more accurate and useful interpretations of surface ice conditions. The current state of the art in passive microwave imaging is well represented by NORDA's Ka-band Radiometric Mapping System (KRMS), which was developed by the Naval Weapons Center, China Lake, California. The KRMS operates at a center frequency of 33.6 GHz. Three parabolic, vertically polarized antennas with a beamwidth of 1.1° effectively scan 50° to either side of nadir, and a data swath width 2.38 times the aircraft altitude is obtained. Surface resolution is about 5 m for each 300 m of aircraft altitude. The KRMS provides calibrated images of surface or near-surface radiometric temperature (so-called brightness temperatures) distribution. This information is interpreted in terms of sea ice/water conditions. The KRMS can be used to map ice edges, ice concentration, water openings, and variations in ice thickness (Ketchum et al., 1983). In addition, areas of radiometrically warmer first-year ice (210 to 248 Kelvins [K]) are easily discriminated from the radiometrically colder (155 to 200 K) old ice (ice that has passed through at least one summer). Summer melting and erosional processes cause an increase in porosity and a decrease in salinity of the upper layer of the ice, thereby reducing the radiation at 33.6 GHz. The greatest

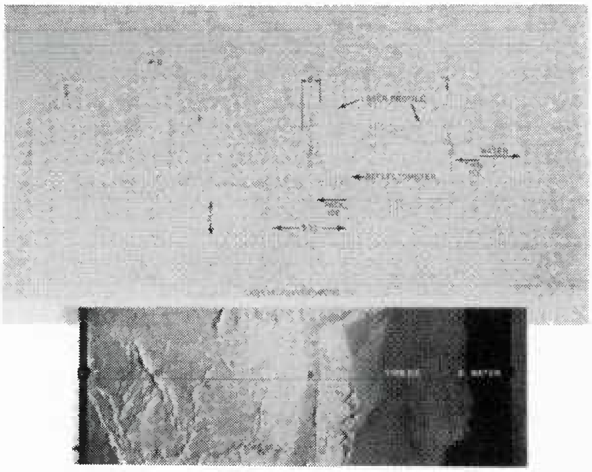


Figure 7.7. Laser and reflectometer profiles of sea ice and water. Aircraft altitude variations have not been removed from the laser profile example. Reflectometer readings are inverted.

disadvantage of the KRMS is the ambiguity relative to detection of pressure ridging. Figure 7.8 shows a mosaic of KRMS imagery taken over the Chukchi Sea in March 1983. Radiometrically cooler (lighter toned) multiyear ice floes are shown in a matrix of first-year and new ice cover. Warmer splotches on the floes represent frozen (fresh water) melt ponds. Variations in brightness temperature seen in the matrix ice are related to variations in ice thickness. The thicker first-year ice has a higher brightness temperature than the new ice.

Active Microwave: Both side-looking airborne radar (SLAR) and SAR are extremely useful in sea ice studies. The expression, synthetic aperture, refers to a technique by which digital signal processing is used to numerically (synthetically) create a much higher azimuthal resolution than would be expected from the actual size of the antenna. Radar systems can be used during any weather and lighting situation, and they provide a broad area, high-resolution image that can be made map-correct. The image also provides a very different view of sea ice that is easy to interpret by the trained observer. Essentially the radar return is largely controlled by the nature of the upper surface of the ice. If the surface is rough with respect to the radar wavelength, scattering occurs and a strong return is received at the antenna, which results in a bright image. If the ice is smooth with respect to the wavelength, the energy is reflected away from the aircraft, resulting in a dark image. The nature of the image portrayal of sea ice conditions is strongly dependent on ice surface geometry and the radar frequency (or wavelength) used. Several radar frequencies have been used for sea ice surveillance and in some cases multifrequency, multipolarization SARs have been used. The L-band (25-cm wavelength) SAR does not discriminate first-year ice from multiyear ice on the basis of backscatter (which is low in both cases), but L-band is a good frequency for displaying the network of ice ridges and hummocks (Ketchum, 1983). The higher radar frequencies (K-, X-, and C-band, 1- to 7.5-cm wavelengths) clearly discriminate first-year ice from multiyear ice because of the relative high backscatter from the somewhat porous upper layer of the multiyear ice, but at times pressure ridges and hummocks are unidentifiable because of high background clutter with these higher frequencies. A dual-frequency SAR (such as X- and L-band) offers the best solution for the optimum extraction of sea ice information. Figure 7.9 shows a simultaneously collected X- and L-band imagery taken by a Canadian SAR-equipped Convair 580 in March 1979 in the Beaufort Sea. The imagery shows a portion of T-3 and surrounding ice about 5.5 months after the SEASAT SAR imagery shown in Figure 7.5 was taken. Many of the same sea ice features can be seen on the SEASAT and the airborne imagery. Both channels (as seen in Fig. 7.6) have advantages and disadvantages in interpretation. L-band more clearly shows the distribution of the high return areas of deformed ice because of the contrasting low returns from the background areas of first-year ice and the multiyear ice floes. The more rounded shapes of the multiyear floes enable their distinction from the angular areas of first-year ice; however, these differences (shape) are not as amenable to computer analysis techniques as backscatter differences. The X-band imagery clearly

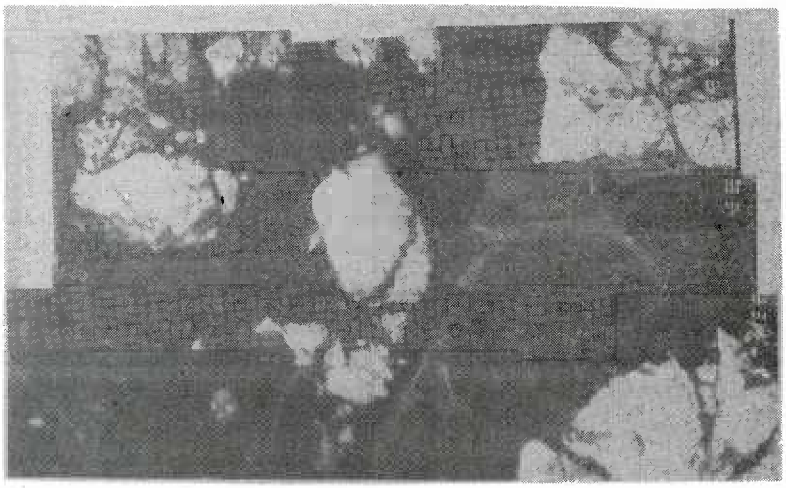


Figure 7.8. Mosaic of KRMS imagery taken over the Chukchi Sea in March 1983. Radiometrically colder (light toned) multiyear floes sharply contrast with first-year ice and new ice background. Thicker first-year ice is radiometrically warmer (darker toned) than new ice. Dark spots on multiyear ice floes represent frozen (fresh water) melt ponds.

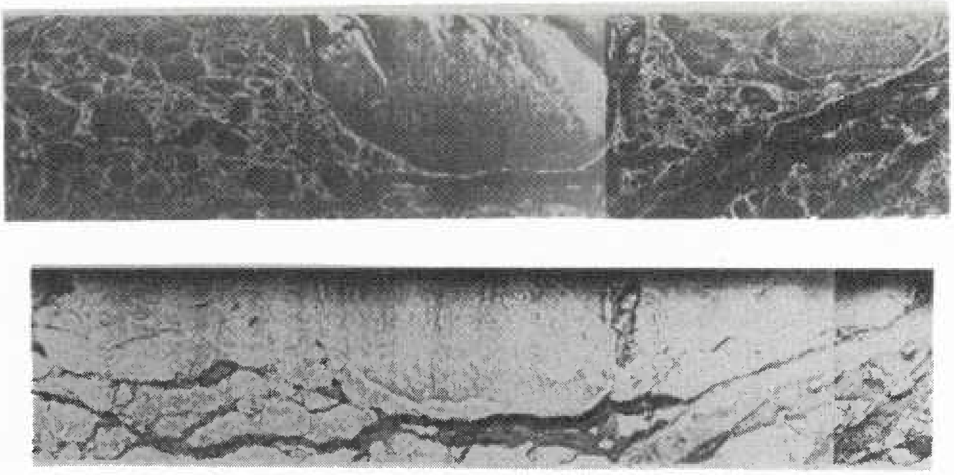


Figure 7.9. Airborne L-band (top) and X-band (bottom) imagery taken over the Beaufort Sea by Canadian SAR-equipped Convair 580 in March 1979. L-band imagery more clearly shows the distribution of high backscattering ridges and rubble because of low returns from background first-year and multiyear ice. X-band imagery distinguishes multiyear from first-year ice because of the high backscatter from the multiyear ice. Backscattering may obscure ridges on X-band imagery.

distinguishes first-year ice from multiyear ice because of backscatter differences. However, the distinction of ridges and rubble zones using X-band SAR will not always be clear because of background clutter often associated with this shorter wavelength.

Buoys

Expendable instrumented buoys have been designed to produce a long time series of data, and include drifting buoys and unmanned buoys on the ice. These buoys generally have to be installed in their desired initial location, but consideration is being given to aircraft or ship delivery systems that do not require personnel on the ice. Such instruments have been used to measure atmospheric parameters, as well as ice and oceanographic parameters. Data are received by telemetry to aircraft or by satellite link. The Polar Research Laboratory, Inc. (PRL), of Santa Barbara, California, built most of these expendable buoys. PRL has substantial experience in delivery systems (Buck, 1979, 1982) and data systems for expendable instruments on and near the ice. Adaption to unusual sensors or data requirements can be built on this experience.

Air Droppable Rams (ADRAMS) Buoy: The ADRAMS buoy (Brown and Kerut, 1976) was developed to provide remote tracking of drifting sea ice near the Arctic coast. The NOAA Data Buoy Center spearheaded this program because of its wide experience in developing data buoys for the open ocean, as well as for the Arctic. PRL performed the design, development, and fabrication. The air-droppable feature was used to reduce the high cost of deployment inherent to manual installation and to provide access to deployment areas and seasons of the year previously unsuitable. ADRAMS contains a 401.2-MHz transmitter and suitable digital encoding to allow it to be received by the NIMBUS-6 satellite. This satellite contains a random access measurement system (RAMS) package. The RAMS determines the position of the ADRAMS buoy to an accuracy better than 5 km through Doppler measurements of the received signal. The buoy is deployed by its own parachute and is designed to survive and properly orient its own antenna on any type of terrain. The 80-lb package contains batteries for 7 to 8 months of operation at surface temperatures as low as −50°C. Although the original ADRAMS was designed for tracking only, it has been modified to incorporate a capability for sensor data telemetry. The RAMS in the NIMBUS-6 satellite accepts 32 bits of data from each transmission.

SYNRAMS Buoy: In 1975, as part of the Arctic Ice Dynamics Joint Experiment (AIDJEX), PRL developed and installed 10 data buoys in the Arctic Ocean north of Alaska (Greene, 1982). These buoys, called SYNRAMS (Synoptic Random Access Measurement System), sensed air temperature, barometric pressure, and the ambient noise level in 4 one-third-octave frequency bands selected between 3.2 and 1000 Hz. The hydrophones were 30 m below the surface. Samples were taken every three hours and were stored in memory for transmission to a satellite in polar orbit.

SYNARGOS Buoy: In 1979, a new satellite data collection/navigation system (called ARGOS) began operation with eight times the data capacity of the 1975 system (Greene, 1982). ARGOS, in operation on NOAA satellites, relays sensor data from diverse platforms and provides information useful in computing accurate positions of the platforms. The original ambient noise buoy design (SYNRAMS) was modified to collect data from 11 one-third-octave frequency bands between 5 and 1000 Hz, with sampling every three hours. These buoys, called SYNARGOS, sampled the noise simultaneously. Data analyses included investigating relationships between noise level and drift rate, the levels in one frequency band with respect to another, and the effects, if any, of the locations of the buoys (e.g., shallow water versus deep water, or Eurasian Basin versus Amerasian Basin).

The project demonstrated a modern technique for collecting data systematically from a wide variety of sensors. For example, barometric pressure, air and water temperature, geomagnetic field, and radiation field may be measured from unattended drifting platforms.

Wideband SYNARGOS Buoy: In modifying the SYNARGOS acoustical capabilities, PRL extended the frequency range from 1 kHz to 50 kHz (Greene, 1982). The original SYNARGOS buoy was housed in a single cylindrical tube with the transmitting antenna at the top and the hydrophone suspended from the bottom. It was designed for installation through a hole augered through an ice floe. However, for the wideband SYNARGOS buoy (Fig. 7.10) the design was modified so that the system could be installed in an open water area (Fig. 7.11) that would freeze with the onset of winter. The surface flotation unit, which includes the antenna, is filled with foam and includes a collar at the water line. This unit is designed to withstand the crushing forces of the freezing water without hazard to any electronics. A 60-m, double-armoured coaxial cable connects the surface unit to the subsurface electronics housing, which contains all the electronics plus the batteries. Beneath this unit are the two hydrophones, suspended 30 m below the surface with a 25-lb weight.

Both units are 20.3 cm in diameter and are fabricated from an aluminum cylinder with a 6-mm wall. The surface unit cylinder is 112 cm long, and the subsurface electronics housing is 104 cm long.

The wide-band SYNARGOS buoys transmitted for 1 sec each hour during 5 hours per day. The ARGOS computer located the buoy with an accuracy of 1 km or better. At high latitudes, each of the two satellites supporting ARGOS was likely to "see" the buoys on each pass, for a total of up to 28 times per day.

Buck et al. (1979) describe a concept that employs a SYNARGOS data buoy that is designed for air drop into open water leads of opportunity, is powered for up to 1 year, and uses the TIROS-N ARGOS system for position and data recovery. The configuration of the buoy,

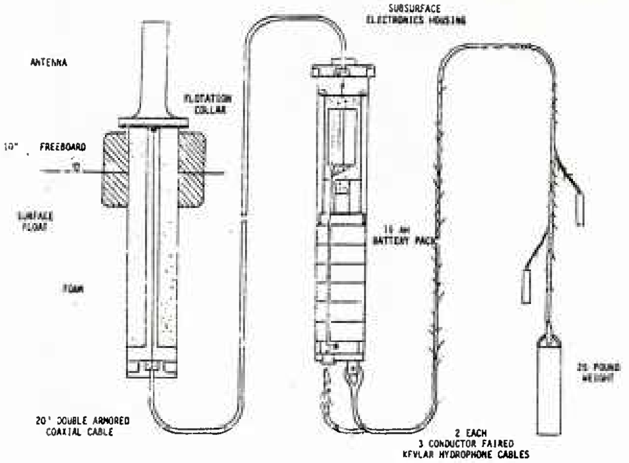


Figure 7.10. Wide-band SYNARGOS buoy assembly.

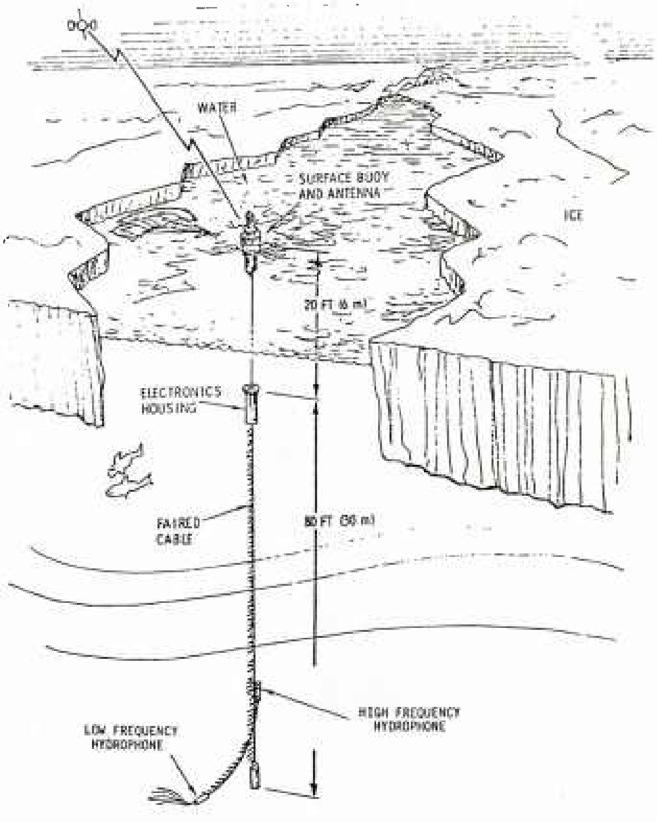


Figure 7.11. Artist's rendering of the wideband SYNARGOS installed in an open water lead.

called LAD (Lead Air Droppable), is described along with the results of preliminary Arctic field tests of the concept.

Arctic Ocean Data Buoy Program: The Polar Science Center, University of Washington, as part of the United States contribution to the First GARP Global Experiment, established an array of automatic data buoys in the Arctic Basin early in 1979. The objectives of this buoy program, which has continued for several years, are to provide measurements of surface atmospheric pressure over the basin and to define the large-scale field of motion of the sea ice.

The buoys' basic internal components are a radio transmitter, timing and coding logic, a pressure sensor, a temperature sensor, and a battery power supply. These are contained in a spherical hull of 62-cm radius. The buoys are dropped by parachute from a C-130 (Hercules) aircraft at designated latitudes and longitudes.

Submarines

Although underice submarine cruises in the Arctic are not conducted frequently, when they do occur they offer the unique opportunity to collect data otherwise unobtainable and, in some cases, in areas generally inaccessible by other means. Hopefully, underice operations, which will include the collection of scientific data, will be more frequent in the future.

Bibliography

Brown, W. P. and E. G. Kerut (1976). Air Droppable RAMS (ADRAMS) Buoy. *Oceans* 76, MTS-IEEE, 13–15 September.

Buck, B. M., S. P. Burke, and J. O. Anderson (1979). *Arctic Lead-Airdrop Data Buoy*. PRL Technical Report No. 18, July.

Buck, B. M. (1979). *Feasibility Tests of the Use of the Tri-Turbo-3 Aircraft for Arctic AXBT Drops*. PRL TR 19, July.

Buck, B. M. (1982). *Aircraft for High Arctic Deep-Penetration Flights, Manned Station Support and Data Buoy Installations*. PRL Tech Note No. 82, November.

Greene, Charles R. (1982). *Wideband SYNARGOS Ambient Noise Data Buoy*. PRL TR 43, September.

Ketchum, R. D., Jr. (1984). SEASAT SAR Sea Ice Imagery: Summer Melt to Autumn Freeze-up. *Int. Journal of Remote Sensing*, v. 5, n. 3, pp. 533–544.

Ketchum, R. D., Jr., L. D. Farmer, and J. P. Welsh, Jr. (1983). *K-Band Radiometric Mapping of Sea Ice*. Naval Ocean Research and Development Activity, NSTL, Mississippi, NORDA Technical Note 179.

Ketchum, R. D., Jr. (1983). Dual Frequency Radar Ice and Snow Signatures. *Journal of Glaciology*, v. 29, n. 102.

Radl, Charles J. and James P. Welsh (1983). *Open Water and Thin Ice Detection in the Arctic Marginal Ice Zone using Reflectometer Signal Analysis*. Naval Ocean Research and Development Activity, NSTL, Mississippi, NORDA Technical Note 209.

Weeks, W. F. (1982). Sea Ice: The Potential of Remote Sensing. *Oceanus*, v. 24, n. 3, Fall.

8. Adapting to the environment

Introduction

The Franklin, Karluk, Jeannette, and many other Arctic ventures resulted in disaster and loss of human life. One of the reasons was insufficient knowledge and understanding of the Arctic environment.

Less than a hundred years ago the success of an Arctic expedition was measured by the number of survivors. Today, loss of human life is not common in the Arctic expeditions. The success of expeditions (especially scientific expeditions) is measured by different criteria. These criteria are related to the design of the experiments and measurement systems used to obtain data in a unique environment. Thus, the interplay of man and his machines (measurement systems) is the key ingredient for success in Arctic scientific investigations. Both man and machine are adversely affected by low temperature operations characteristic of the Arctic region.

Man

Man's physiology was not designed for the Arctic environment. A compromise is established by adaptation, preparation, and avoidance. Working in an environment where the most dominant element is low temperature can be accommodated both physically and mentally. A high level of physical fitness is correlated with a more efficient cardiovascular system. Transport of a greater volume of blood provides for greater insulation and improved distribution of oxygen around the central heat-producing regions of the body.

Four physiological aspects must be considered to limit discomfort from the cold: prevention of body-heat loss, improved heat production, distribution of body heat to critical areas and areas most susceptible to cold injury, and management of moisture (i.e., perspiration, etc).

When placed in the Arctic environment, a person from a temperate climate will not have the physical adaptations of a person already living in an Arctic climate. For example, the warm Eskimo hand is well known and repeatedly described by early Arctic explorers. The Eskimo has adapted to the cold, which allows him to maintain higher skin temperatures that, in turn, enable him to lose more heat from the hand. Through prolonged exposure to cold, it appears that some modification in the structure and location of blood vessels can occur, which results in greater flow of blood through the hands. Over several generations, those individuals with the more efficient vascular systems have been more successful in the environment.

A higher level of physical fitness for the Arctic investigator will permit more vigorous and prolonged activity, which results in increased heat production and more personal comfort. The degree of personal discomfort is not dictated by physical adaptation alone, but also by mental adjustment. A person must recognize and accept some discomfort caused by the cold.

Preparation, primarily in the form of clothing, can allow the Arctic to become a relatively comfortable working environment. Comfort comes from a more complex utilization than just the amount of insulation required to combat specific ranges of temperatures and winds. The amount of clothing required depends upon the individual's level of physical activity. For example, a person may need four times more insulation while sleeping than while active. Improved materials and design have helped to regulate and standardize Arctic clothing. Because overdressing, when coupled with vigorous physical activity, increases perspiration, clothing must allow for the regulation of body heat. This results in increased heat loss due to the wet skin and clothing and consequent loss of insulation value of the clothing. The key is to dress in layers such that outer layers can be removed or added to regulate body heat loss. Properly trained personnel should not suffer cold injury.

Avoiding prolonged exposure to cold can supplement adaptation and preparation. Care in developing the experimental design and the sampling plan can often result in a data collection effort near a heated shelter or working in a shelter constructed over a hole in the ice. Transportation by helicopter rather than on foot, etc., can also be used to conserve body heat/energy. The extent of this luxury can be determined by the nature of the experiment and experience of the personnel. The following summarizes considerations and proven techniques for working in a cold environment.

General

- Cold is not as bad as most believe.
- With good equipment and adequate knowledge, man can work in the cold with reasonable comfort.
- There is little danger of serious injury from the cold if knowledge and common sense prevails.
- The cold can create an attitude of quitting but should not be taken as an excuse for not working.
- A strong positive attitude should be maintained to increase personal efficiency.

Care of self

- Keep skin pores open by washing and remaining as clean as possible.
- Increase caloric intake (high-energy foods to provide metabolic fuel for heat production).

- Increase fluid intake, as more water is lost through perspiration and urination.
- Take extra care of small injuries because clotting and healing are slower in the cold. Cuts and bruises tend to require more time to heal and absorb.

Care of clothing

- Avoid and eliminate, where possible, oil, grease, and dirt on clothing because their insulation value will be reduced by increasing conductive heat loss.
- Most clothing must be kept dry for the insulation to work.
  - –Brush off snow from clothes and boots outside, then hang clothes high in a heated shelter.
  - –Leave moisture-saturated items outdoors, allow moisture to freeze, knock off the ice, then complete drying in heated shelter.
  - –Drying of socks and small items of clothing can be done satisfactorily in a goose-down sleeping bag overnight even though one is not sleeping in a heated shelter.
- Ventilation is needed to limit the amount of perspiration that remains in the clothing's insulation and can cause an increase in conductive heat.
- Opening zippers and removing outer layers of clothing when physical activity is increased will allow improved heat dissipation and improved moisture management.

Suggested list of personal equipment, supplies, and clothing

Minimum requirements; more may be needed for extended stay

Parka (down-filled): 1
Thermal boots (during wet or extreme cold conditions): 1 pair
Mukluks (dry conditions only): 1 pair
Boot liners: 2 pair
Wool socks: 4 pair
Wind pants: 1 pair
Wool pants w/suspenders: 2 pair
Wool shirts: 2
Watch cap (wool): 1
Wool scarf: 1
Long underwear (wool or cotton): 2 pair
Arctic mitts (for very cold): 1 pair
Leather gloves w/wool liners: 2 pair each
Snow goggles or dark sunglasses: 2 pair
Flashlight (small)
Chapstick and sunscreen
Medication required (ample supply—expected stay + 5 days)
Interesting literature for storm days
Sewing kit
Paperwork (tickets, orders, checks, etc.)
Motion sickness pills, if necessary (for helicopter travel)
Extra pair of prescription glasses/contacts
Weatherproof field books/pencils

Regular clothing (quantity will depend on length of stay)

Shoes/boots—leather/rubber bottom, leather top w/felt liner or insulated leather boots
Socks—cotton, wool, silk, poly prop
Briefs
Pants
Shirts (flannel or wool)
Handkerchiefs
T-shirts
Wool sweater (turtleneck)

Toiletries/overnight kit

Wash cloth, bath towel, hand towel
Soap, toothbrush, toothpaste, etc.
Hand lotion
Hairbrush

Extras (nice to have)

Cameras/lenses/film
Alarm clock
Lighter/matches
First-aid kit (personal)
Candy bars (eaten in the field, good energy source, as well as calories to burn for heat production)
Ear plugs (work around helicopter and aircraft)
Jacket for near-freezing conditions

First aid

Some injuries and sickness are unique to the Arctic environment. Others are merely more common under normal Arctic living conditions.

- Carbon monoxide poisoning can result from burning fuel in a closed environment without sufficient ventilation. Symptoms are dizziness, headache, nausea, and drowsiness. The treatment is artificial respiration if breathing has stopped and, in all cases, plenty of fresh air and oxygen if available.
- Hypothermia or below-normal body temperature has its best treatment in prevention. When a person cannot maintain his normal body temperature, several

situations may arise. The first, and most common, is local cold injury known as frost-bite. Frost-bite should not be a serious or common problem among experienced Arctic investigators. However, minor frostbite occurs and serious frostbite may have to be combatted in a survival situation. In mild or moderate cases where body temperatures are above 20°C, treatment is simply a slow warming (e.g., using body heat of a warm hand) of the frozen area and paying particular attention to maintaining a clean area to prevent infections. In extreme cases, the severity of the injury may not be determined for several hours or even days, as it may take this long to see the effects of tissue and circulatory damage. Do not rub the frost-bitten area because tissue damage can be increased. The person must not smoke or in any other way impair circulation.

A more severe result, general hypothermia, commonly leads to circulatory and cardiovascular disorders, such as ventricular fibrillation, which is usually fatal without trained medical attendance and facilities. Hypothermia causes, signs, symptoms, prevention techniques, and treatments are shown in Table 8.1.

- Snow blindness is the result of high-intensity light striking the eye from below, where it is unprotected by eyelids or lashes. Northern sunlight has a higher-than-normal percentage of ultraviolet rays (less atmospheric filtering) and the usual low sun angles. Sunburn to exposed areas (face, etc.) must also be considered. These factors, coupled with a high surface albedo from snow and ice, can cause the cornea to be painfully inflamed or actually burned if the eye is not shielded. The best protection is to wear sunglasses or snow goggles, which will stop this light from getting through. Symptoms are a burning, gritty sensation in the eyes (like sand), nausea, pains in the neck and back, and headache. The eyes very often tend to water. Preferred treatment is to keep the

Table 8.1. Hypothermia

Causative Factors	Signs (observed by others)	Symptoms (felt by victim)	Prevention	Treatment
Poor physical condition	Poor coordination	Intense shivering	Good rest and nutrition prior to cold exposure	REDUCE HEAT LOSS: Shelter the victim from wind and weather
Inadequate nutrition and hydration	Slowing of pace	Muscle tensing	Continued intake of food	Insulate him from the ground
Thin build	Slurring/slow speech	Fatigue	Water-windproof clothing	Replace wet clothing with dry
Nonwoolen clothing	Amnesia (mild or severe)	Feeling of deep cold or numbness	Emergency survival equipment	Put on windproof, waterproof gear
Inadequate protection from temperatures, wind, rain, snow	Irrationality, poor judgment	Poor coordination	Early bivouac in storm or if lost	Increase exercise level if possible
Wetness	Hallucinations	Stumbling	Exercise to keep upbody's heat production	ADD HEAT: Put in warmed sleeping bag
Exhaustion	Blueness of skin	Poor articulation (slurring/slow speech)		Hot drinks
	Dilation of pupils	Disorientation		Heat from external source (heater, etc.)
	Decreased heart and respiratory rate	Decrease in shivering, followed by rigidity of muscles		Huddle for body heat. Add heat to body (trunk) primarily with limbs receiving less heat, i.e., warm internal organs and major volume of blood first.
	Weak or irregular pulse	Blueness of skin		
	Stupor	Slow, irregular or weak pulse		

person indoors, resting, with eyes bandaged and away from bright light until recovered (usually 2 to 4 days).

- Chapped lips are common due to the dry air, high winds, and extreme cold. A number of standard creams can be used for chapped lips, but if none of these are available a little bit of Vaseline or butter will keep the lips soft and oily so that the condition will be minimized. Adequate attention to hydration must also be considered.

Keeping warm

The most important rule about keeping warm is to do something about getting warm before you get too cold.

- Running in place, pounding the feet, wiggling the toes 100 times, opening and closing the hands in the mitts with as much pressure as possible for 100 times will all help keep the body warm by increasing blood flow to the extremities.
- Much heat is lost from the head and face; thus, they should be covered so that as little as possible is unprotected, especially if one is feeling cold.
- Running in deep snow and vigorous exercise produces heat. Thus, manual labor can be an aid to comfort in the Arctic.
- While one is sleeping, the face should be covered as much as possible, but breath should be exhaled out of the bag so that the bag will not get wet. The moisture from the breath, i.e., warmer body temperature air from lungs, has higher water vapor content, condenses on the bag, and thus decreases its insulation value.
- Eating and exercising in a sleeping bag will warm you up. Do not just lie there and shiver.

Survival

With the possibility of fire, hostile weather conditions, and even ice break-up, everyone venturing to the Arctic should draw from the experience of others and have an indoctrination in Arctic survival.

Fire safety is extremely important. Because of heat introduction, often in the form of open flames, and the presence of flammable vapors from refueling engines and heaters, great care must be exercised.

While traveling all but very short distances in the Arctic, personnel should always travel in pairs and always be prepared to camp for a minimum of a few days. The possibility of ice separating, sudden storms, or mechanical difficulties might make further travel unsafe.

Survival kits should always be available and close to the living area, but not so close that they could be lost if the shelter burned. The NORDA Polar Oceanography Branch kit is designed to support 2 persons. The minimum survival kit contents follow.

- One full set of outer clothing (boots, mukluks with liners, down-wind pants, mittens or gloves, and parka)
- One ice axe or hatchet
- Two sleeping bags (down mummy type)
- One waterproof sheet, 20 feet x 20 feet
- Strobe light
- Whistle
- Signal mirror
- One flashlight (5-year shelf life battery)
- Printed ground to air signal and survival, etc., information
- First-aid kit
- Heater/fuel/matches (MSR (multifuel) stove with two 1-liter containers for fuel, striker, and tourister cook kit). (Fuel containers are shipped empty, are filled on scene, and are tied to the outside of the banded survival box.)
- Emergency locator transmitter/(121.5 beacon and 243 MHz) with 282 voice transmit/receive)
- Food (freeze-dried and ready to eat, 3 days, two meals/day/person)
- Flare kit (day/night and pencil type)
- Rope (1/4-inch nylon line, 50 ft)
- Polypropene line (25 ft) tied to outside of box to help locate in snowdrifts and to pull box like a sled.
- Snow knife
- One closed cell foam pad (to sleep on)
- Compass (for dead reckoning if travel is necessary)
- Two-man tent
- Survival kit, pocket size (2)
- Toilet paper (1 roll)
- Thermal blanket (space blanket)
- GI can opener

The above items are packed in a box approximately 18 inch x 14 inch x 48 inch, banded, and labeled ''SURVIVAL'' black letters on an orange background.

At least one person in the ice party should be familiar with Arctic survival techniques, i.e., first aid, building shelters from available materials (snow and ice), identification of old ice for drinking water, over-ice travel, signaling, etc.

The following two lists are a suggested contents for a first-aid kit and an abbreviated description of the use of the contents of the kit (Forgey, 1979). Some items and descriptions of use have been omitted from the original reference because they are not useful in the Arctic (e.g., very little risk for snake bite in the Arctic). Forgey (1979) also provides a recommended list for a number of prescription medications in addition to the nonprescription items shown below.

Contents of a suggested first-aid kit (2–10 persons, 1–3 months)

Schein otic drops: 1 oz
Yellow oxide of mercury opth 1%: 1/8 oz
Percogesic: 48 tablets
Chlorpheniramine 4 mg: 25 tablets
Splinter forceps
Wirecutters, side-cutting type
Bandage scissors or operating scissors
Bisacodyl 5 mg: 10 tablets
Tinactin cream 1%: ½ oz
Camaloz tablets: 20–40 tablets
Dibucaine ointment 1%: 15 grams
Q-tips: Box of 300
Triple antibiotic ointment: 15 packets
Bacid capsules: 20–30 capsules
Pseudoephedrine 30 mg: 50 tablets
Povidone-iodine prep pads: 10 pads
Bandages 1 x 3 inch; tape 1 inch x 10 yd
Gause pads 3 x 3 inch: 3 pads
Gauze roll 3 inch x 10 yd: 1 roll
Elastic bandage 4 inch x 5½ yd: 1
Butterfly closures, medium: 10
Moleskin 12 x 2 inch: 1
Aspirin 5 grain: 25 tablets

The medications "should be restricted to healthy young adults, not suffering from hypertension, diabetes, glaucoma, kidney disease, liver disease, thyroid disease, or ladies who are pregnant or nursing. Prior to embarking upon a wilderness expedition where such use of these items may be required, all participants should have a physical exam to ensure their exclusion from the above categories" (Forgey, 1979). Consider review of inoculations, especially tetanus.

Thorough medical and dental examinations are recommended for each individual prior to departure for the Arctic.

Abbreviated directions for use of suggested first aid kit contents (2–10 personnel, 1–3 months)

Note: For extended trips where medical help is not available.

Earache: External infection (hurts when pushing on tragus (knob at front of the outer ear)).

- Schein otic drops: 4 drops every 4 hours.
- Triple antibiotic ointment: Apply with Q-tip three times daily.
- Percogesic: 2 tablets every 4 hours for pain as needed.
- A prescription oral antibiotic should be taken.

Middle-ear infection (runny nose and head congestion present).

- Chlorpheniramine 4 mg: 1 tablet 4 times daily.
- Pseudoephedrine 30 mg: 2 tablets 4 times daily.
- A prescription oral antibiotic should be taken.

Eye inflamed: Check for foreign body (speck). If foreign body seen, use

- Percogesic: 2 tablets 1 hour before attempting removal.

No foreign body, whites of both eyes inflamed—probably conjunctivitis.

- Yellow oxide of mercury 1%: Apply every 4 hours.

Snowblindness—Bandage eyes (exclude light) and rest.

- Percogesic: 2 tablets every 4 hours for pain as needed.

Nasal congestion, sinus

- Chlorpheniramine 4 mg: 1 tablet 4 times daily.
- Pseudoephedrine 30 mg: 2 tablets 4 times daily.

Sore throat, laryngitis

- Percogesic: 1 or 2 tablets every 4 hours for pain, fever.

Severe cough

- Hydrate; Percogesic, as above for pain.
- With high temperature, an oral prescription antibiotic should also be taken.

Abdomen

- Vomiting—Meclizine 25 mg: 1 tablet every 8 hours as needed.
- Heartburn—Camalox: 2 to 4 tablets, dissolved in mouth.
- Cramps and diarrhea—Bacid capsules: 2 capsules every 4 hours as needed.
- Appendicitis—Without medical help, move as little as possible to prevent rupture of appendix.
  - Percogesic: 2 tablets every 4 hours for pain.
  - Meclizine 25 mg: 1 tablet every 8 hours for nausea.
  - No food; small amounts of Gatorade, etc., as tolerated.
  - Prescription antibiotic should be provided.
  - Arrange for medivac by helicopter, etc.

Constipation

- Bisacodyl tablets 5 mg: 1 or 2 tablets.
- Adequate fruit in diet should prevent constipation.

Cuts, burns

- Scrub wound with povidone-iodine prep pad.
- Cover wound and 2–3° burns with triple antibiotic ointment.

Skin infection, dirty wound

- Local heat, 15 minutes every 4 hours to raise abscess to a head. Lance to allow draining—do not squeeze. Continue hot soaks and dressing changes as required.

- Pack abscess with povidone-iodine prep pad.
- Triple antibiotic ointment on bandage with each change.
- A prescription oral antibiotic should be taken.

Skin rash, itch

- Dibucaine ointment 1%: Apply 2–3 times daily.

Fungal infections

- Tinactin cream: Apply 3 times daily.

Pain

- Percogesic: 1 or 2 tablets every 4–6 hours.

Bladder infection

- Push fluids, 8 quarts daily. Acidify urine by drinking cranberry juice, taking Vitamin C, etc.

Machines

All machinery in the Arctic (engines, drills, sleds, electronics) requires specific adaptations, preparations and, in some cases, sheltering from the low temperatures and blowing snow.

Condensation, resulting from carrying a piece of cold equipment from outside into a warmer, more humid shelter, often causes problems. It is especially true of electronics where corrosion caused by condensation on relays, contacts, and switches renders a piece of gear inoperative. Cold temperatures affect electrical components by stiffening and cracking insulation and plastic covers, and by stiffening switches, solenoids, relays, etc.

Electric and combustion motors present problems after cold soak as a result of loads imposed on them by an increase in lubricant viscosity in the driving mechanisms. Increased friction and metal fracture in components is highly possible due to differential contractions in dissimilar metals caused by low temperatures.

Power required to start or operate motors and equipment is often drawn from storage batteries. Their efficiency is greatly reduced when exposed to low temperatures. At −40°C the capacity of a typical storage battery is reduced to 25% of its capacity at −20°C. A cold battery cannot be charged as rapidly as one at higher temperatures. The charging rate at −20°C is one-sixth of that under ordinary conditions.

Constant precaution is essential when operating in the Arctic, and many preventive measures are necessary that otherwise would not be of concern in normal climes.

Arctic machinery is often heavier, more costly, and more often designed for simplicity and reliability than its temperate climate counterparts. With a very limited supply of spare parts available and conditions for maintenance often inhospitable, a general rule of thumb for the Arctic is "if a piece of equipment can determine the success or failure of a mission—take two."

Polar bears

Polar bears are dangerous. Their behavior is unpredictable. Personnel working and camping on sea ice in the Arctic must be prepared to encounter polar bears. The primary approach to dealing with polar bears is to avoid unexpected contact and to prevent their attraction to work/camp areas.

Be alert and look before exiting a shelter or walking off, and maintain some type of alarm system around work/camp areas. Be very careful with garbage; anything that might smell like food, even gum wrappers and chewing tobacco, could attract the polar bear's keen sense of smell. Keep garbage in tight containers or otherwise disposed of properly. Keep food in containers that minimize available scent, and do not keep food in the shelter where you will sleep. Garbage dump, food storage, and latrine areas should be visible from camp shelters because these are the primary areas of interest to the bears.

When walking on sea ice, especially in deformed ice areas, be alert for bears that are sleeping or hunting. Never travel alone or without at least one firearm for the traveling party. Polar bears are very curious, very quiet, very fast, and agile on ice; they are excellent swimmers. In general, a distance of 50 m between you and a bear does not threaten or pose a challenge to the bear. At this distance you can attempt to scare the bear away by shouting or firing an explosive flare between you and the bear. In addition, you can back (facing the bear all the time) slowly away. If the bear stands sideways to you, it is probably frightened and will begin to move away.

Killing the bear is almost always avoidable. However, if the bear faces you, lowers its head, makes a hissing sound, and makes a rush of four to ten paces in your direction and then stops, it is annoyed. If your separation is less than 50 m, you must stand your ground and be prepared to shoot to kill. If the rush toward you is stopped within 20 m, do not hesitate to shoot. If you cannot avoid killing the bear, try to shoot it in the low neck region if it is broadside to you, or in the low center neck between the shoulders if it is facing you. Do not try a shot to the head unless you are absolutely sure of a hit. It is better to hit one of the two recommended areas and stop the bear. Then use a second shot to kill.

Recommended firearms are .30-06 bolt action rifles (with open sights) and 12-gauge pump action shotguns. The .30-06 bullet should be soft point of 200 grains or greater. The shotgun should be loaded with rifle slugs and 00 buckshot. Because of the cold temperatures, semi-automatic rifles, shotguns, and pistols are not recommended.

The weapon must be completely degreased, stored with magazine loaded, chamber empty in a fired state, safety off in a canvas case outside the shelter door. Rubber band and plastic bag can be placed over the muzzle to prevent plugging of the barrel by snow, ice, etc.

Each firearm must be fired in the field to be sure it is working. All camp personnel must be completely familiar with the operation and safety of each weapon. Usually one weapon per two people is sufficient, with one of the two people responsible at all times for that weapon. Hand guns (revolvers) are not recommended because, except in the hands of a very experienced marksman (with large caliber handguns), they pose more real danger to the personnel in the camp from accidental discharge than the danger posed by a polar bear.

References

Boswick, J. A. (1981). *Emergency Care.* W. B. Saunders Co.

Coffey, M. F. (1956). *Aids to Working in the Cold.* Defense Research Northern Laboratory, 200-9-56-56-2619, Canada Defense Research Board.

Forgey, W. W. (1979). *Wilderness Medicine.* Indiana Camp Supply Goods, Pittsboro, Indiana.

Guide to Clinical Care in Isolated Environments (1983). ITEST, Inc., 2550 M. Street, NW, Suite 300, Washington, DC 20006.

Handbook for Pilots (1985). Aircraft Owners and Pilots Association, Fredrick, Maryland.

Smith, T. G. (1980). Danger! Polar Bear! *Polar Continental Shelf Project*, cat. no. M78-6/1980E, Dept. of Energy, Mines and Resources, 880 Wellington St., Ottawa Ont., K1A OE4.

Wilkerson, J. A. (1978). Medicine for Mountaineering. *The Mountaineers*, Seattle, Washington.

9. Logistics

Introduction

Three factors distinguish logistic operations in the Arctic. The first is the very often hostile environment. In the Arctic, the environmental elements can drastically vary from one area and season to another. Each area (such as the ice fields, glaciers, tundra, river deltas, mountainous terrain, and pack ice) can present a wide range of temperature, wind, visibility, etc., conditions.

The second factor is the time element. Because one or more methods of transportation are unusable or are uncertain for varying periods of time during the year (i.e., caused by weather, ice, mud, etc.), long lead times for positioning supplies and larger reserves for contingencies are required than is normal for similar operations in more temperate zones. It is frequently necessary to preposition materials at forward bases almost a year in advance to ensure their availability when needed.

The third factor is related to the scale of the effort to be supported. Polar operations require an appreciably greater support effort than similar operations in less rigorous climates and terrains. In the Arctic Basin and immediately adjacent land areas, 16 tons per man year is a reasonable estimate for support requirements, as compared to 4 tons for similar tasks in the temperate zones. Drifting stations have required up to 25 tons per man per year.

Logistics planning

Careful planning and organization is mandatory for any support operation conducted in the polar regions. Polar operations are completely dependent upon their logistics system, not only for the success of the mission, but for their very existence.

Broad planning factors may be used for preliminary estimates, but each operation must be planned in detail. The logistic planning must fit the size and peculiar requirements of the particular expedition.

An axiom of polar-region logistic planning is that one must get along without anything not absolutely needed. Attempting to fill every conceivable need can disastrously overburden the logistics system. It can also be disastrous to provide too little; therefore, operations must be planned so that field parties have adequate supplies to fall back on in such emergencies as storms, transportation delays, etc. To strike a proper balance is not an easy task. The following points should be remembered when planning a mission.

- Select proven items whenever possible. Just because it checks out in the laboratory cold chamber does not mean it will work in the field.
- If you really need an item, TAKE TWO!
- Keep life support items, such as, heaters, stoves, lamps, and generators, as simple to operate, maintain, and repair as possible.
- Package equipment in shipping containers that are small and light enough to be handled by one or two men.
- Maintain a complete and detailed inventory, with copies at both ends of the supply line. Each shipping container should be clearly marked as to the contents or purpose and referenced in the inventory.
- Prepare shipping containers so that they can be delivered by all available transport modes, i.e., determine the minimum size and/or weight of individual units for all types of transportation systems and use the smallest size possible. This may be totally impractical for some large items such as diesel generators, acoustic sound sources, long acoustic arrays, winches, etc., which may have to be shipped by an alternative mode or will require special handling arrangements, etc., requiring longer lead times.
- Consumable or perishable items should be purchased as close to the final destination as possible. This may result in higher per unit costs, but is cost effective in the long run as it saves time and reduces the risks of loss and spoilage.
- Use existing resources where possible. Do not reinvent the wheel! Identify those locations where support facilities and equipment are already in place and use them to your advantage. Table 9.1 lists some support bases/locations/facilities that are available for Arctic operations.

Staging of cargo

There are two basic types of expeditions in the Arctic: small and large. The small scientific party will normally rely on scheduled commercial forms of transportation (scheduled airlines and military airlift command) to ship materials from their home base to jump-off sites in the Arctic. Transport to the final destination may be by land vehicle, helicopter, light fixed-wing aircraft (ski, wheel, or floats) or occasionally by boat.

Large expeditions (20 or more) will require quantities of supplies that make scheduled commercial air transport impractical, thus requiring contract air freight, barge, long haul truck, or surface ship support. Drifting ice camps will often probably rely on a combination of icebreaker and large aircraft for support.

Table 9.1. Support bases for polar operations.

Facility	Country	Military/Civilian	Accommodations	Food	Communications	Schedule Airline	Fuel	Hangar	Maintenance	Harbor	Runway Length x Width Elevation	Navigation AIDS Frequency	VHF, UHF Frequencies
Akureyri	I	M	A	A	Y	?	A	?	?	?	20-02 6693 x 98 6	NDB 319 HJ	Tower 118.2, 292.7 Radar 118.7
Alert	C	M C	A	A	Y	N	N	N	N	N	048-228T 5500 x 150 100 *	NDB 305 LT	126.7, 5680 HF
Andoya	N	M C	Y	Y	Y	Y	Y	?	Y	Y	15-33 8000 x 148	NDB 343.5 ANY	118.2, 254.25
Barrow	US	C	Y	Y	Y	Y	Y	Y	Y	Y	6-24 6500 x 150 44	LOC 109.1 NDB 248 IEY TACAN 281 YIR	123.6
Barrow DEW	US	M	A	A	Y	N	A	Y	N	Y	25-205 4993 x 142 13	Same as Barrow	123.6
Barter Island	US	M	A	A	Y	Y	A	Y	Y	Y	6-24 5000 x 150 5 *	NDB 308 BTI	126.2 236.6
Danmarks Havn	D	?	?	N	?	?	N	N	?	Y	?	?	?
Eureka	C	C	A	A	Y	N	A	Y	N	Y	105-285T 5200 x 150 256 *	NDB 205 YBJ	122.8
Frobisher Bay	C	C	Y	Y	Y	Y	Y	Y	Y	Y	18-36 9000 x 200 110	NDB 262 F	122.2 126.7
Gander	C	M C	Y	Y	Y	Y	A	Y	?	?	4-22 10500 x 200 496	NDB 280 QX 264 Q LOC 109.5 I-QX	APR CON 128.5, 384.5 Tower 118.1, 236.6 Ground 121.9, 275.8
Goosebay	C	M C	Y	Y	Y	Y	Y	Y	Y	Y	8-26 11,050 x 200 60	LOC 110.3 I-YR TACAN 212 Y	APR CON 119.5, 267.1
Inuvik	C	C	Y	Y	Y	Y	Y	Y	Y	Y	5-23 6000 x 150 224	NDB 254 EV	APR CON 122.3, 132.4 126.7
Jan Mayan	N	C	10	Y	Y	N	A	N	?	N	6-24 5200 x 130	NDB 362 JAN	
Keflavik	I	M C	Y	Y	Y	Y	Y	Y	Y	Y	11-29 10,015 x 200 169	NDB 364 OK LOC 109.5 IKF	APR CON 119.3, 363.8 Tower 118.3, 257.8
Longyear-Byen	N	C	40	Y	Y	Y	A	N	Y	Y	?	?	?
Mould Bay	C	C	A	A	Y	N	A	N	N	N	92-272 T 5400 x 200 40	NDB 230 YMD	122.8

Key:

I = Iceland C = Canada N = Norway D = Denmark US = United States

Y = Yes N = No ? = Unknown T = True A = by prior arrangement * = gravel may not be usable during melt season

Table 9.1. Cont'd.

Facility	Country	Military/Civilian	Accommodations	Food	Communications	Schedule Airline	Fuel	Hangar	Maintenance	Harbor	Runway Length x Width Elevation	Navigation AIDS Frequency	VHF, UHF Frequencies
Nord	D	M	20	N	N	N	A	N	?	N	?	?	?
Prudhoe Bay (Deadhorse)	US	C	Y	Y	Y	Y	Y	Y	Y	Y	4-22 6499 x 180 57	NDB 234 PVQ SCC 113.9 CH86	123.6, 119.2 (ATIS)
Resolute	C	C	20	Y	Y	Y	A	Y	N	Y	167-347 T 6500 x 200 221 *	NDB 350 RB LOC 110.3 I-RB	122.2, 126.7
Sondrestrom Fjord	D	M C	Y	Y	Y	Y	Y	Y	Y	Y	10-28 9200 x 200 165	NDB 382 SF	APR CON 118.3, 363.8 Tower 126.2, 236.6
Thule	D	M	Y	Y	Y	Y	Y	Y	Y	Y	15-33 10,000 x 150 251	LOC 109.5 I-TL	APR CON 134.1, 363.8
Tromso	N	C	Y	Y	Y	Y	A	Y	Y	Y	01-19 6562 x 148	VOR 113.8 TRO	123.7, 118.3
Tuktoyaktuk	C	C	A	Y	Y	N	A	Y	N	Y	86-266 5000 x 100 15 *	NDB 380 UB	122.2, 126.7

Key:
I = Iceland C = Canada N = Norway D = Denmark US = United States
Y = Yes N = No ? = Unknown T = True A = by prior arrangement * = gravel may not be usable during melt season

Equipment must be packaged and staged with due consideration of the time constraints for each transport system. Transportation networks, staging areas/Arctic support bases, and aircraft capabilities are discussed in the following sections.

Transportation networks

Air: Commercial airlines maintain scheduled passenger and freight service to many areas throughout the Arctic (Table 9.1). The predominant aircraft is currently a cargo/passenger version of the Boeing 737. Actual configuration varies between airlines. Therefore, it is necessary to consult the specific airline for the size and weight specifications of cargo. Aircraft utilized for service to outlying areas are generally smaller, such as twin otters, etc.

The military provides scheduled passenger and cargo service to the following bases that have been used as staging areas.

Alaska: Eielson AFB (Fairbanks)
Elmendorf AFB (Anchorage)
Canada: Goose Bay AB (Labrador)
Greenland: Sondrestrom AB
Thule AB
Iceland: Keflavik N.A.S.

Road: Highways in the Arctic region are generally restricted to local networks extending from a port or airfield to service local facilities. However, several are suitable for over-the-road, long-haul truck transport.

Alaska: Pipeline service road from Fairbanks to Prudhoe Bay, graded gravel suitable for year-round transport of materials to the Deadhorse Prudhoe Bay Complex.

Canada: The Dempster Highway has been extended north to Inuvik, graded gravel suitable for year-round use. An ice road from Inuvik to Tuktoyaktuk is maintained from December–March, depending on the ice conditions.

Sea lift: Logistic support of large operations or extended programs may require that supplies and equipment be positioned at forward sites. Sea lift is perhaps the most economical means available for large-scale logistic efforts. Sea lift routes service many of the northern bases and are listed below.

Alaska:	Barge convoys transport fuel and other cargo from Seattle, Washington, and Anchorage, Alaska, to Barrow, Prudhoe Bay and Barter Island. Deliveries are made from August to September.
Canada:	Barge traffic north on the Mackenzie River begins in July and continues through September. Service is provided to Tuktoyaktuk and Barter Island. Icebreakers are used to resupply Eureka and other sites throughout the Canadian Archipelago. Icebreaker-escorted resupply ships provide service to Goosebay, Labrador, Frobisher Bay, and Resolute.
Greenland:	U. S. Navy sealift vessels provide resupply for Sondrestrom Fjord and Thule AB during August–September.
Iceland:	Ship transport is available throughout the year to Keflavik and Reykjavik.
Norway:	Northern bases (Tromso, Andyoa, etc.) are served by commercial ships year round.

Staging areas

Figure 9.1 shows the locations of the major staging areas in the Arctic region. Table 9.1 lists some of the types of support available at these locations.

Limited aircraft maintenance support exists at Thule AB and Sondrestrom AB in Greenland, Keflavik NAS in Iceland, and at Goosebay AB in Labrador, Canada. Hangar space or shop support vary at other locations (Table 9.1) and should be checked out individually as a part of the planning phase.

The former Navy Arctic Research Laboratory facilities are available through private contractors and can provide food and lodging along with limited transportation. Private contractors at Deadhorse, Alaska, can provide lodging, food, fuel, maintenance, fabrication shops, and some survival support items.

The Canadian Polar Continental Shelf Project maintains support facilities at Tuktoyaktuk, Resolute, Alert, and Mould Bay, as well as several minor sites. They can provide lodging, food, fuel, and support equipment with a one-year advance notice.

Aircraft capabilities

Aircraft support will vary from light fixed-wing and helicopters to large transports such as C-130s. Tables 9.2 and 9.3 list most of the aircraft suitable for polar operations and their characteristics.

Support of drifting ice camps

Icebreakers of the Polar and Wind Class have been used to transport men and material and to assist in establishing drifting ice stations. They have been used up to about 80°N, depending on the ice conditions at the time. Entire camps for 10–20 personnel have been transported and logistically supported using icebreakers. Larger camps (more than 20 personnel) located in the Arctic Basin have been established using a combination of fixed-wing aircraft and helicopters. Larger camp operations usually require that suitable runways be established and maintained.

Parachute drops and free drops have been used to supply remote drifting stations, ice survey parties, and adventurers traveling to the North Pole.

Submarines

The submarine has not been used to establish or support ice camps; however, the possibility should be considered.

Summary

This overview of logistic support for Arctic operations is designed to highlight the need for careful planning and practical thinking, and to provide examples of some available resources. However, one is strongly advised to consult specific documentation and experienced personnel concerning construction materials and methods, airfield preparations on sea ice, air drop techniques, communications, navigation, and aircraft operations, etc., during the planning phase to ensure complete safety and a high probability of success. The bibliography provided and sources recommended are not exhaustive but are adequate.

Bibliography

Airfields on Floating Ice Sheets (1956). SIPRE Report 36, CRREL, January.

Arctic Flying (1979). ONR.

Arctic Logistics Summary (1983). Untersteiner, University of Washington.

Arctic Logistics Support Technology (1971). Arctic Institute of North America. November.

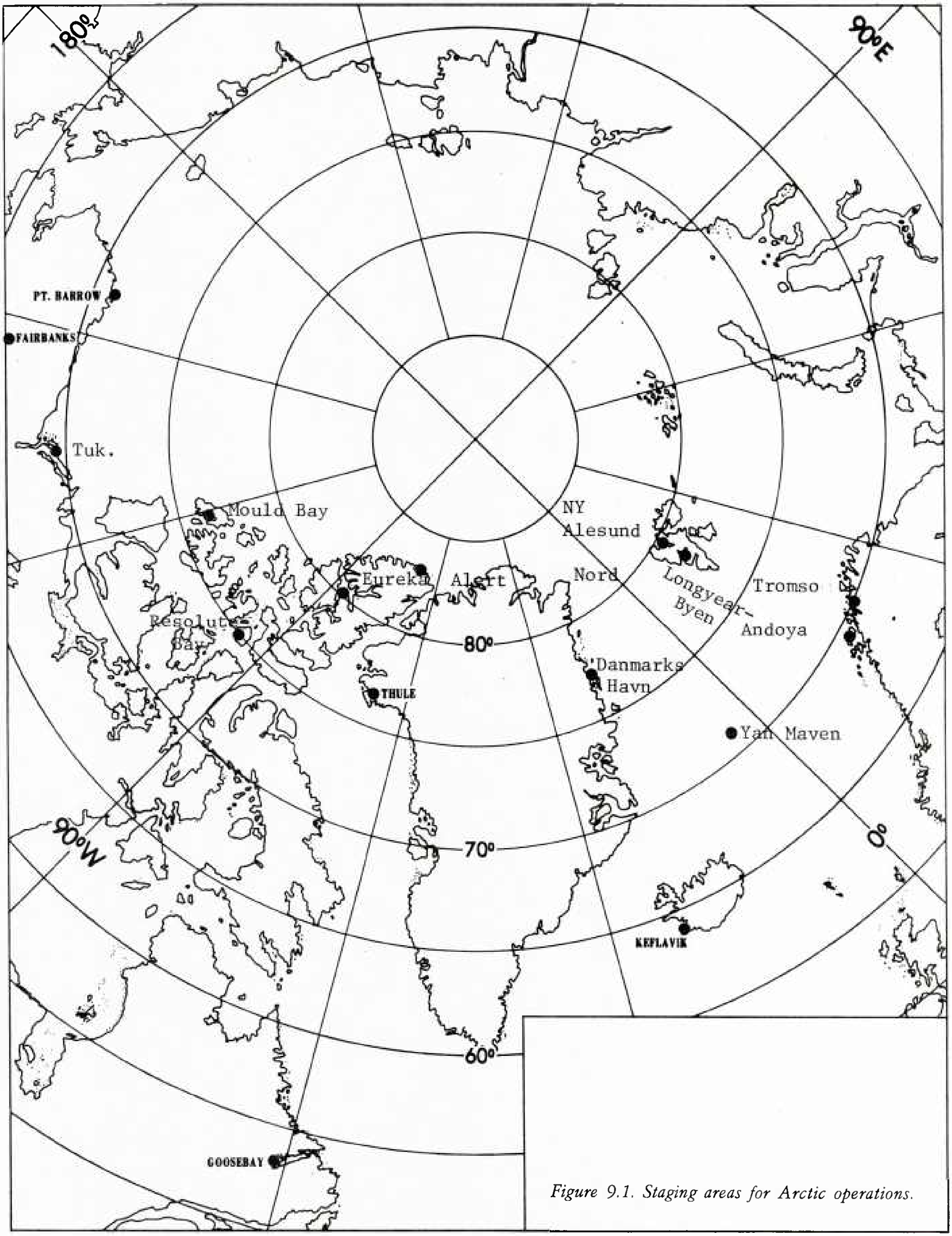


Figure 9.1. Staging areas for Arctic operations.

Table 9.2. Rotary wing aircraft for Arctic use.

Aircraft MFR and Model	Cruise Speed	Payload	Ski Equipped	Engine Type	Max. Range (miles)	Arctic Use
Aerospatiale						
Alouette II	95	1,300	Yes	Turbine	290	Extensive
Lama	100	2,400	Yes	Turbine	320	Limited
Alouette III	100	2,300	Yes	Turbine	308	Limited
Gazelle	163	1,840	Yes	Turbine	405	Extensive
Puma	160	7,950		Twin-Turb.	341	Limited
Bell						
206B	100	1,620	Yes	Turbine	341	Extensive
204B	110	3,000	Yes	Turbine	150	Limited
205A	120	4,180	Yes	Turbine	311	Extensive
212	125	5,330	Yes	Twin-Turb.	261	Extensive
Boeing						
105C	140	2,260	Yes	Twin-Turb.	350	Limited
Hiller						
FH 1100	100	800	Yes	Turbine	135	Extensive
12E	80	1,340	Yes	Recipro	146	Extensive
Hughes						
500C	160	1,640	Yes	Turbine	350	Extensive
Sikorsky						
S58T	115	5,000	No	Twin-Turb.	170	Extensive
S561N	140	7,990	Yes	Twin-Turb.	545	Extensive
S64E	100	20,000	Yes	Twin-Turb.	350	Limited

Table 9.3. Fixed wing aircraft for Arctic use.

Aircraft Designation	Trade Name	Cruise Speed (knots)	Payload (lbs)	Ski Equipped	Floats	Engine Number and Type	Maximum Range (NM)	Runway Surface Required	Minimum Operating Temp.	Arctic Use
Cessna 180	Skywagon	125–142	500	Yes	Yes	1-Piston	600	Any Firm	−30°F	Extens.
Cessna 185	Skywagon	132–145	1,140	Yes	Yes	1-Piston	600	Any Firm	−30°F	Extens.
DHC-2 Beaver	Beaver	105–115	800	Yes	Yes	1-Piston	700	Any Firm	−30°F	Extens.
DCH-3 Otter	Single Otter	110–116	800	Yes	Yes	1-Piston	1,900	Any Firm	−30°F	Extens.
DHC-6 Twin Otter	Twin Otter	120–160	3,500	Yes	Yes	2-Turboprop	800	Any Firm	−45°F	Extens.
DHC-5 Turbo Beaver	Turbo Beaver	140–160	1,500	Yes	Yes	1-Turboprop	300	Any Firm	−45°F	Extens.
DHC-7 Otter-7	Dash 7	220–233	6,500	No	No	4-Turboprop	1,500	Any firm	−45°F	New
DC-3	R4D & C-47	130–10	5,000	Yes	No	2-Piston	1,200	Hard-Prepared	−40°F	Extens.
Tri-Turbo-3	DC-3 with PT6A-1 engines	200 (EST)	10,000 (EST)	Yes	No	3-Turboprop	3,000	Any firm	−40°F	New
C-117 D	Super DC-3	130–150	5,200	Yes	No	2-Piston	1,200	Hard-Prepared	−25°F	Extens.
C-121	Constellation	220–240	20,000	No	No	4-Piston	3,500	Hard-Prepared	−25°F	Extens.
C-141	Starlifter	435	64,000	No	No	4-Jet	6,500	Hard-Prepared	−45°F	Limited
Helio H-295	Helio Courier	143–156	1,200	Yes	Yes	1-Turbocharged	550	Any Firm	−30°F	Extens.
Helio AU-24A	Helio Stallion	140–180	1,200	Yes	Yes	1-Turboprop	600	Any Firm	−40°F	Extens.
DHC-5	Buffalo	225–233	18,000	No	No	4-Turboprop	2,000	Hard-Prepared	−50°F	Limited
C-130	Hercules	300	35,000	Yes	No	4-Turboprop	3,600	Hard-Prepared	−45°F	Extens.

Arctic Research Logistics Support Handbook (1972). National Science Foundation, December.

DoD Flight Information Publication (Terminal) (1986). *Low Altitude Canada and North Atlantic*, 21 November 1985 to 16 January 1986.

Janes' *All the World's Aircraft.*

Naval Arctic Manual (1970). ATP17 (A), January.

Polar Regions Atlas. (1978). C. I. A., May.

Sater (1969). *The Arctic Basin.* Arctic Institute of North America, August.

Ships and Aircraft of U. S. Fleet Naval Institute (1981). Press.

U.S. Government Flight Information Publication (Terminal) (1986). *Alaska*, 21 November 1986 to 16 January 1986.

Appendices

The following appendices are included as a brief introduction to each of the marginal seas within the Arctic Ocean. The format for each sea will allow quick-look comparisons in oceanography, circulation, sea ice, and climatology. The charts of monthly average ice cover were derived from information supplied by the Naval Polar Oceanography Center, Suitland, Maryland.

Appendix A: Barents Sea

The boundaries of the Barents Sea are
north—Franz Josef Land;
south—Russia, Finland, Norway Coastline;
east—Novaya Zemlya;
west—Spitsbergen and Bear Island.

Oceanography

The Barents Sea lies between 70° and 80°N and has an area of 1.3 x 10^6 km^2. Since it lies entirely over the Continental Shelf, it is shallow and has a mean depth of approximately 230 m.

The cyclonic movement of the Barents Sea water results in a temperature regime subject to great variations while it moves from the southwestern section into the northeastern section of the sea. The warm Atlantic water, which has temperatures from 4°C to 12°C and salinity about 35 ppt, is found over most of the southern and western Barents Sea. The actual eastward and northward extent varies over the years, but in general there is a pronounced change to 0°C in the vicinity of Bear Island as it mixes with local waters. The surface salinity falls to 32–33 ppt. Small tongues of Atlantic water enter the Barents Sea from the Arctic Basin at depths of 150–200 m through the deep straits between the islands.

Circulation

The Barents Sea has a general counterclockwise circulation pattern as shown in Figure 2.1 of the main text. The Norwegian Coastal Current and the Norwegian Atlantic Current merge to form the relatively warm and saline North Cape Current. This current splits into many smaller branches, one of which (the Murman Coast Current) is responsible for the generally ice-free conditions of the coastline. In the northern part of the Barents, the Bear Island Current brings down cold, fresh Arctic water from the northeast and meets the warm, saline Atlantic water in the vicinity of Bear Island, forming the frontal region south of Bear Island.

For more information on currents, see *Oceanographic Atlas of Polar Seas, Part II*, Arctic, 1958. U.S. Naval Oceanographic Office, NSTL, Mississippi.

Sea ice

The ice conditions in the Barents Sea are less severe than those of other Arctic peripheral seas at the same latitude. The North Cape Current, which carries warm Atlantic water into the Barents Sea, keeps the southwestern portion ice free all year. Furthermore, ice conditions can be accurately predicted up to three years in advance by measuring the flow rate and temperature of the North Atlantic Drift north of Scotland. In general, maximum ice conditions occur in April when the sea is about 75% ice covered. Ice conditions are at a minimum in September, and occasionally the Barents Sea is totally ice free. Because of the high percentage of open water continually present in this sea, winds and currents have a strong effect on the ice conditions. Monthly average ice cover charts are shown in Figure A.1.

Detailed sea ice information can be found in *Ice Atlas of the Northern Sea Route (U)*, U.S. Naval Oceanographic Office, NSTL, Mississippi, N.O.P. 1202, February 1977. SECRET

Climatology

Warm cyclones from the North Atlantic and cold anticyclones from the Arctic, which pass through the Barents Sea, make it one of the most unstable water masses in the Arctic region. The influence of warmer air masses from the south and remnants of warm Gulf Stream waters cause somewhat higher air temperatures, temperate winters, and abundant precipitation. The active wind regime and the large area of open water provide conditions for storm waves on the southern coasts up to 3.5–3.7 m. Visibility is restricted to less than 2 km about 90 days each year.

Temperatures

Winter −32°C to −15°C
February and March are coldest
Summer 0°C to 7°C
July and August are warmest
Range of mean daily temperatures is −32°C to 7°C.
The lowest recorded temperature is −51°C.
Temperature may be less than −31.5°C 70 days/year.

Winds

Winter	4 to 9 m/sec
Summer	4 to 9 m/sec

Winds may exceed 11 m/sec 34 days/year.

Sea state

Coastal areas experience seas greater than 1.5 m from 10 to 20% of the time. Open ocean areas have seas in excess of 1.5 m from 20 to 50% of the time.

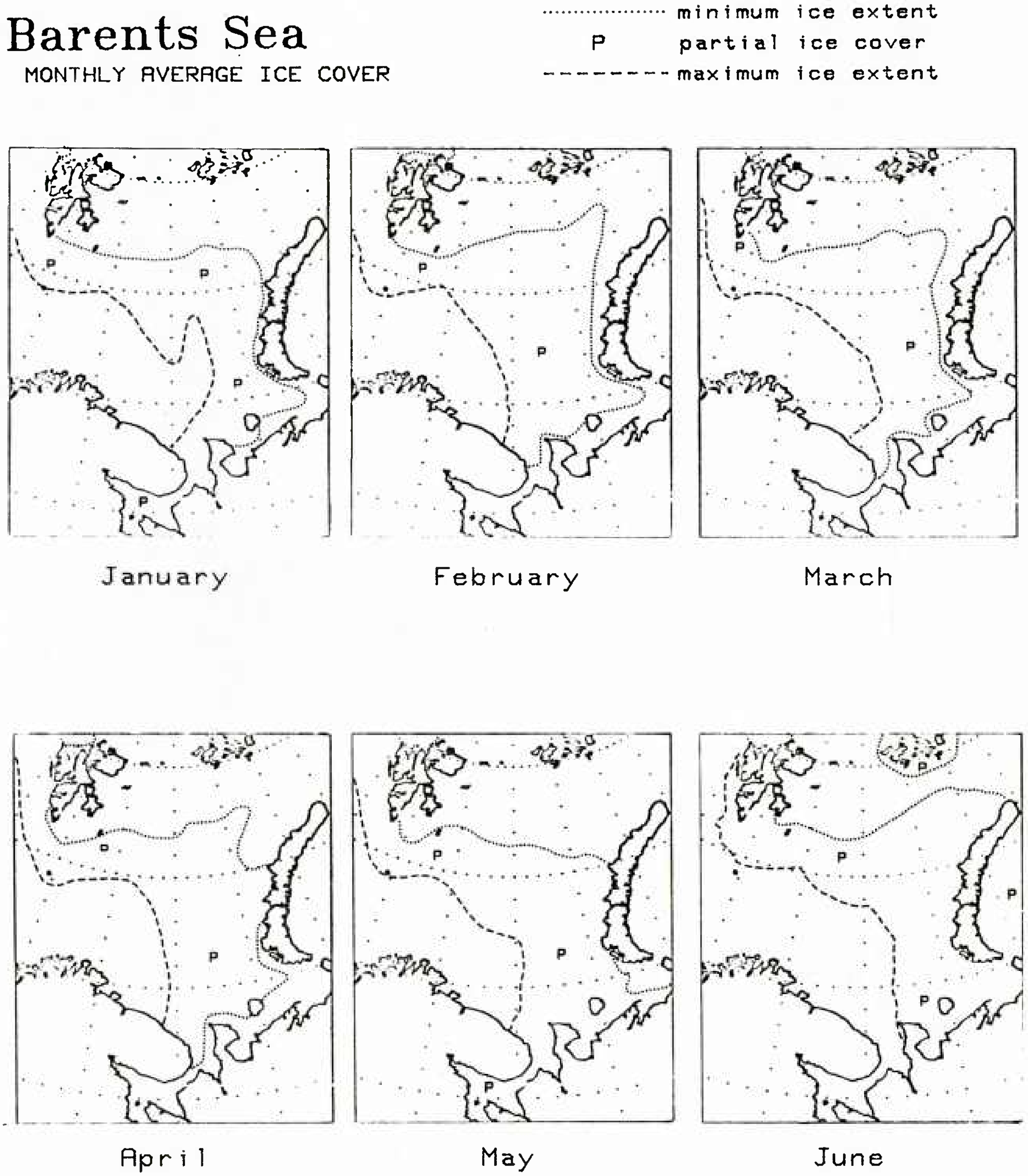
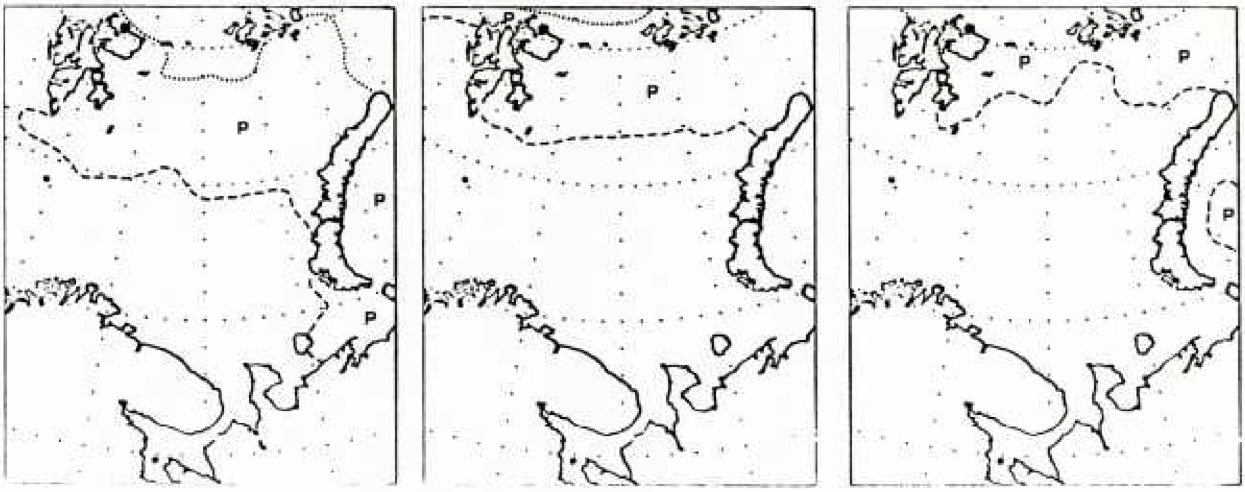
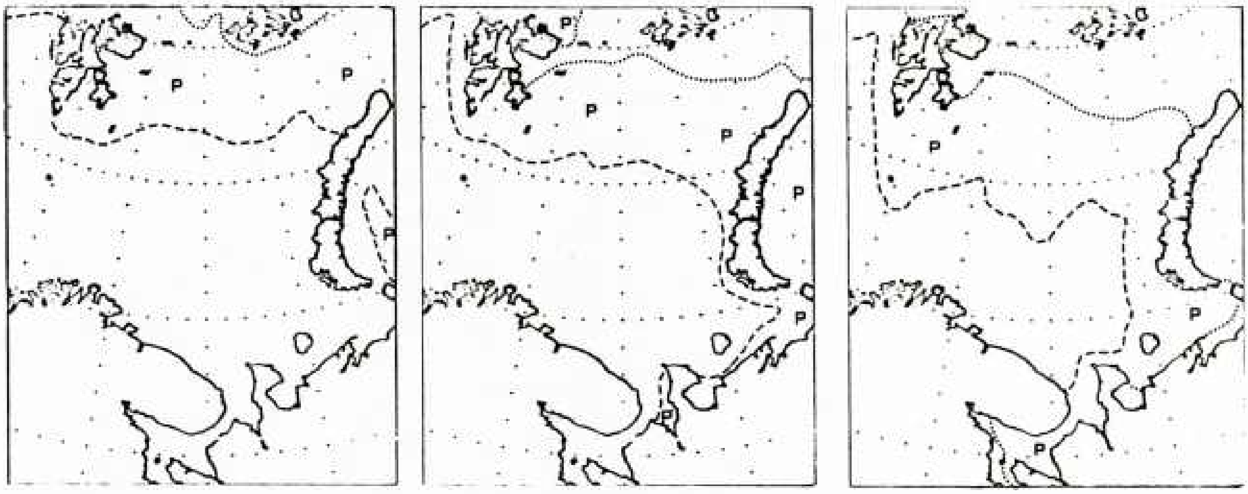


Figure A.1. Barents Sea monthly average ice cover.



July August September



October November December

Figure A.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix B: Beaufort Sea

The boundaries of the Beaufort Sea are

north and west—Pt. Barrow, Alaska, to Cape Lands End, Prince Patrick Island;

south—northern coast of Alaska and Canada;

east—Cape Lands End to Cape Bathurst through Banks Island.

Oceanography

The Beaufort Sea is comprised of four water masses. The surface layer of Arctic water is the only one that undergoes marked seasonal changes in temperature and salinity in response to the freeze and thaw of the pack ice. Beneath the surface water, temperature and salinity distribution are remarkably regular throughout the year. The surface Arctic water is about 100 m thick and is the coldest of the water masses. Its temperature varies seasonally from −1.4°C at the end of summer to −1.7°C at the end of winter; its salinity ranges from 28 to 32 ppt.

Near the base of the surface layer is a warmer interlayer of Pacific water, which enters through the Bering Strait. Underlying the near-surface waters is the Atlantic water mass, which begins at a depth of about 200 m and has a thickness of about 700 m. The Atlantic water is the warmest of the water masses with temperatures above 0°C and occasionally as high as 1°C. Its salinity, which is nearly uniform with depth, varies between 34.0 and 35.0 ppt. Maximum temperature lies between 300 and 500 m, below which there is a gradual decrease to 0°C at the contact with the bottom water mass. The bottom water mass begins at a depth of 900 m and exhibits extremely uniform salinities between 34.93 and 34.99 ppt. Temperature decreases slowly with depth to −0.40°C.

The transition from one water mass to another takes place gradually with depth. In the cold waters of the Arctic the water density is essentially a function of salinity. Therefore, graphs of salinity variation also closely represent density variation as shown in Figure B.1.

Circulation

The circulation pattern in the Beaufort Sea is dominated by the clockwise Beaufort Gyre, which covers the entire Canada and Beaufort Deeps (Fig. B.2). Offshore, these currents flow at a rate of 2–4 km/day. Along the coast, however, currents depend largely on local winds, are highly variable, and may even reverse directions. The clockwise currents of the Beaufort Gyre pile up pack ice along the Canadian and Alaskan coasts, limiting dependable navigation to mid-August through September, and thus account to some degree for the paucity of observational data in this region.

Wave energy is small due to the pack ice, and no significant activity occurs from November to May when the Beaufort Sea is ice covered. Waves along the Alaskan coast usually come from the northeast, which is the dominant wind direction. Easterly winds dominate in summer, but westerlies and northerlies occasionally move the pack shoreward in the summer.

Sea ice

The Beaufort Sea contains a large percentage of multiyear ice that has been carried south in the Beaufort Gyre. Along with these old floes are found pressure ridges, leads, and some first-year ice. There is a relatively warm region of open water in the southeastern Beaufort Sea where varying ice types grow, melt, and freeze as they move past Alaska.

The Beaufort Sea is completely ice covered during April (maximum conditions) with the exception of the constantly forming open water leads and polynyas, which could cover as much as 10% of the total area at any time. These open water areas freeze and/or close to form ice hummocks and pressure ridges. Large hummocks formed near the coastlines of the Canadian Archipelago may drift throughout the sea. Hummocks may reach heights of 9 m and have keels extending to 45 m. Tabular icebergs, which have originated from shelf ice, are occasionally present. The clockwise Beaufort Gyre directs ice motion generally toward the west or west-southwest. Monthly average ice cover for the Beaufort Sea is shown in Figure B.3.

Climatology

The climate of the Beaufort Sea is arctic. Precipitation is light throughout the year; most occurs as snow in

October and November. Some sea ice is present in all months. Visibility is less than 2 km for about 110 days/year. Fog is frequent during the summer months.

Temperatures

Winter $-37°C$ to $-17°C$
Summer $-26°C$ to $12°C$

January and February are the coldest months and July and August are the warmest.

Lowest recorded temperature is $-58°C$.

Temperature may be less than $-31.5°C$ 85 days/year.

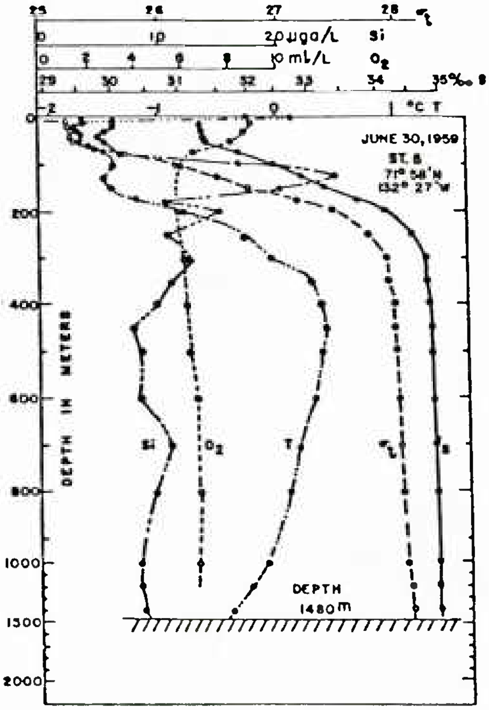


Figure B.1. Vertical distribution of temperature, density, and chemical elements at T-3 station 5 for 30 June 1959 (Kusunoki, 1962).

Winds

Winter 4.5 to 6.2 m/sec W to SW and E to NE
Summer 4.5 to 6.2 m/sec E to NE

Maximum steady wind 35 m/sec.

Winds may exceed 11 m/sec 55 days/year.

Sea state

Seas rarely exceed 1 m due to the presence of sea ice. However, during the summer months seas may exceed 1.5 m during storms, which are usually of short duration.

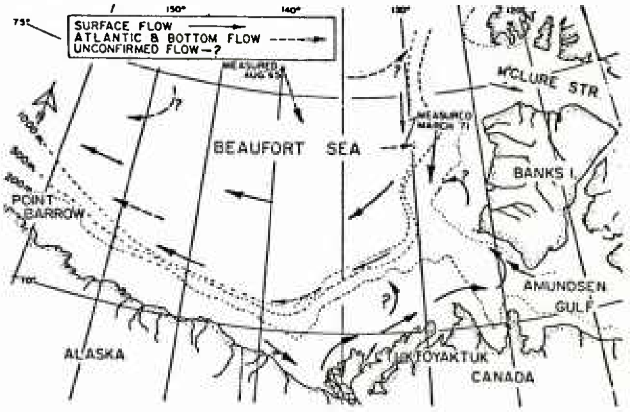


Figure B.2. Horizontal distribution of surface and subsurface water movements (O'Rourke, 1974).

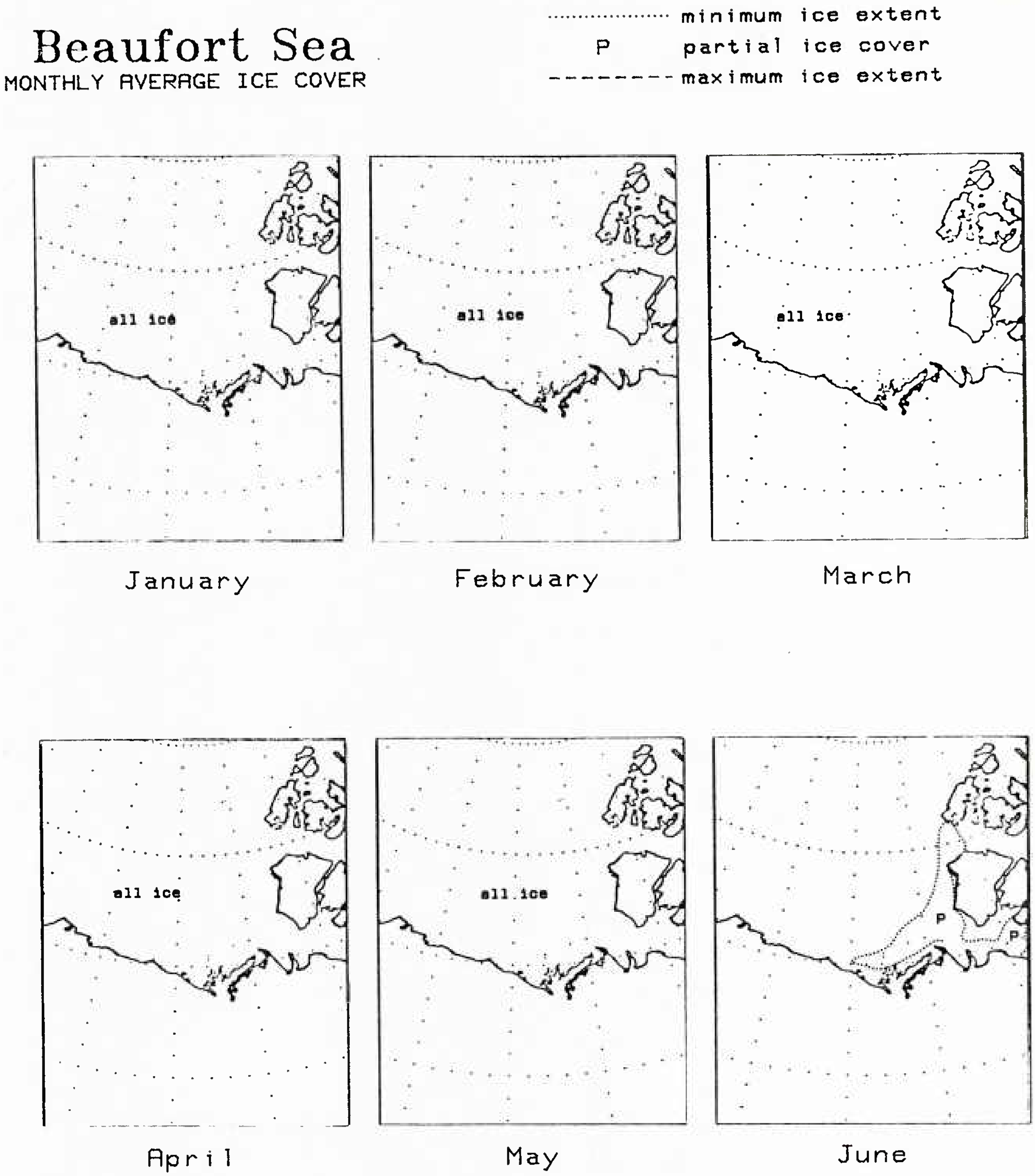
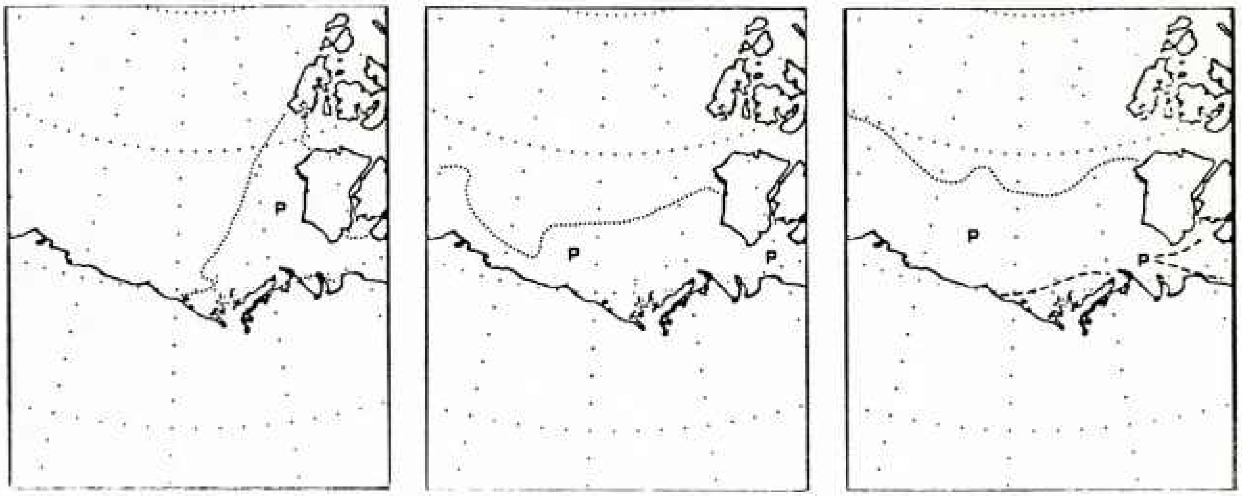
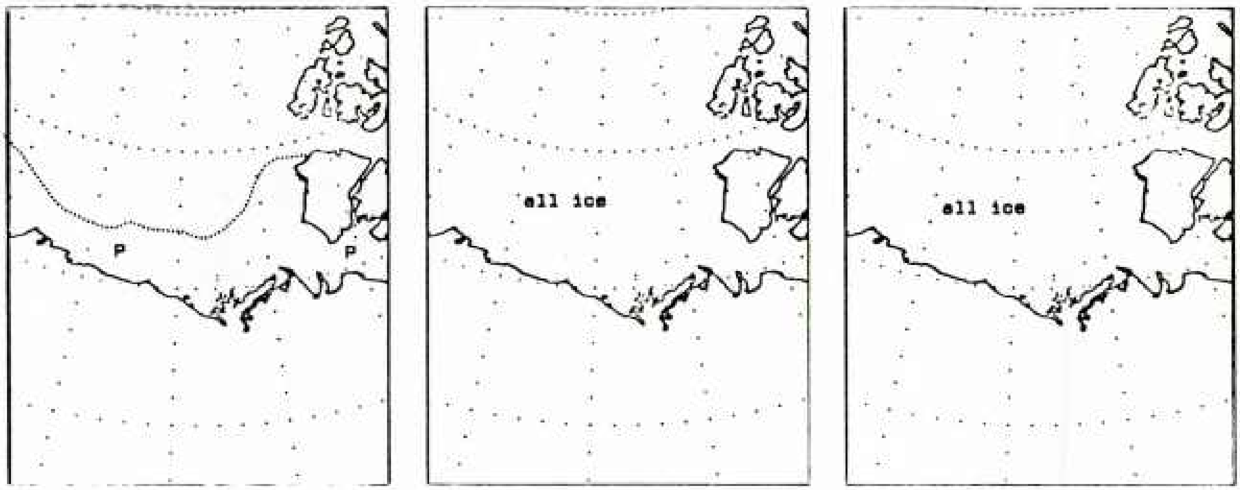


Figure B.3. Beaufort Sea monthly average ice cover.



July August September



October November December

Figure B.3. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix C: Chukchi Sea

The boundaries of the Chukchi Sea are
north—75°N;
south—Arctic Circle (or Bering Strait);
east—a line from 75°N through Wrangel Island to the coast;
west—a line from Pt. Barrow to 75°N.

Oceanography

The physical oceanography and marine biology of the Chukchi Sea are unique because this sea connects the Arctic and Pacific Oceans. This connection is a primary reason the region has a high strategic value as a military chokepoint. Its area is 5.82 x 10^5 km^2.

Physical properties of seawater in this shallow area are influenced by the formation and melting of sea ice, by fresh water outflow from the U.S.S.R., and by the northward flow of water from the Bering Sea. When this region is ice covered the water is isothermal and nearly isohaline because it is slightly more saline at the bottom than at the surface. As the ice melts a thin layer of extremely low-salinity water can be found on the surface over a broad region. In summer, increased river discharge from the U.S.S.R. contributes large volumes of fresh water that mix with more saline water and flow eastward along the coast of the U.S.S.R. as the East Siberian Coastal Current. Warmer, relatively saline Bering Sea water flows northward through the Chukchi Sea, raises water temperatures near Alaska from June to October, and keeps the region just north of Bering Strait ice free as late as November. This region is generally ice covered from December to May, and water temperature is approximately −1.7°C. Higher temperatures first appear near the Bering Strait during June.

In August, mean surface temperatures are less than −1.1°C near the ice and reach 2.2°C in the East Siberian Sea and 10°C in Kotzebue Sound, and cooling begins in late September. The water column remains isothermal from December to May. The temperature structure is modified in the eastern part of the Chukchi Sea as warmer Bering Sea water moves into the region in June.

In summer, mean surface salinity values in the Chukchi Sea vary from less than 26 ppt near regions of fresh-water outflow to 31 ppt in the central part of the region. Melting sea ice and river outflow add fresher water at the surface and can lower surface salinity values to less than 10 ppt near the ice.

The distribution and variation of density in this region are controlled primarily by the highly variable salinity. In winter, density is at a maximum of 25 σ_T. In summer surface density varies from 21 to 24.5 σ_T. Density values can be less than 5 σ_T in the low-salinity water near ice. In summer, sharp density gradients occur between the extremely light surface water and the denser deep water.

The sound channel in this region is weakly developed and ranges in depth from 25 to 50 m. The sonic layer depth is very shallow in summer with maximum depth about 15 m. In autumn, when the region is nearly ice covered, the layer deepens and may reach the bottom.

Circulation

Warm (4°C to 12°C), low saline (<30 ppt) waters enter the Chukchi Sea via the Bering Strait. The flow is swiftest on the eastern side of the strait where speeds of up to 4 knots have been recorded with the flow being strongest during the summer months.

This current flows northward along the Alaskan Coast and divides in the vicinity of the Lisburne Peninsula; part flows westward toward Wrangel Island and part continues along the Alaskan coast to Pt. Barrow. North of Pt. Barrow, the current turns westward with the prevailing Arctic Ocean currents. From the East Siberian Sea, a colder current (4°C to 6°C) with low salinity enters the Chukchi Sea through DeLong Strait south of Wrangel Island. This current flows southeast along the Siberian coast and mixes with the warmer shelf waters as it travels. On exceptional occasions, this current may continue southward through Bering Strait on the western side, but generally the current turns north again before the strait is reached. Along the northern part of the Chukchi Sea, the currents set to the west with the general Arctic Ocean flow. These current patterns are best developed during the summer. General circulation is shown in Figure 2.1 of the main text, but the pattern can vary considerably under wind influence.

Sea ice

The Chukchi Sea is generally ice-covered all year, except for the summer months and with the exception of newly formed open leads and polynyas. These constantly forming openings freeze over and/or close to form new hummocks and ridges whose drafts may extend 30 or 40 m deep. Some deep, drafted hummocks become grounded in the shallow Chukchi Sea. Undeformed first-year ice types in the Chukchi Sea may reach a maximum thickness of 2 m by April. Multiyear ice usually contains many old weathered ridges, many of which may be deep drafted, and is generally 3 or 4 m thick in undeformed areas. Varying amounts of shorefast ice can be found along the Alaskan coast from Cape Lisburne north of Pt. Lay. Pieces of shelf ice or tabular icebergs are uncommon in the Chukchi Sea.

Monthly average ice cover for the Chukchi Sea is shown in Figure C.1.

Detailed sea ice information can be found in *Ice Atlas of the Northern Sea Route (U)*, U.S. Naval Oceanographic Office, NSTL, Mississippi, N.O.P. 1202, February 1977. SECRET

Climatology

The climate of the Chukchi Sea is arctic. Precipitation is light throughout the year. The near-constant ice cover prevents seas from exceeding 1 m, except on rare occasions. The winds are usually light and variable, and shift rapidly in direction with the passage of cyclones. Visibility is less than 2 km for about 180 days/year.

Temperatures

Winter	−32°C to −6°C
Summer	−12°C to 10°C

Range of mean daily temperatures is −32 to 10°C.
Lowest recorded temperature is −45°C.
Temperatures may be less than −31.5°C 20 days/year.

Winds

Winter	4.5 to 7.0 m/sec S to SW
Summer	4.5 to 9.0 m/sec E to SE

Strongest winds normally occur in October.
Winds may exceed 11 m/sec 70 days/year.

Sea state

The Chukchi Sea is usually ice covered in winter and partially covered in summer. Therefore, seas greater than 1.5 m occur less than 20% of the time, and then only during summer months from Barrow, Alaska, south.

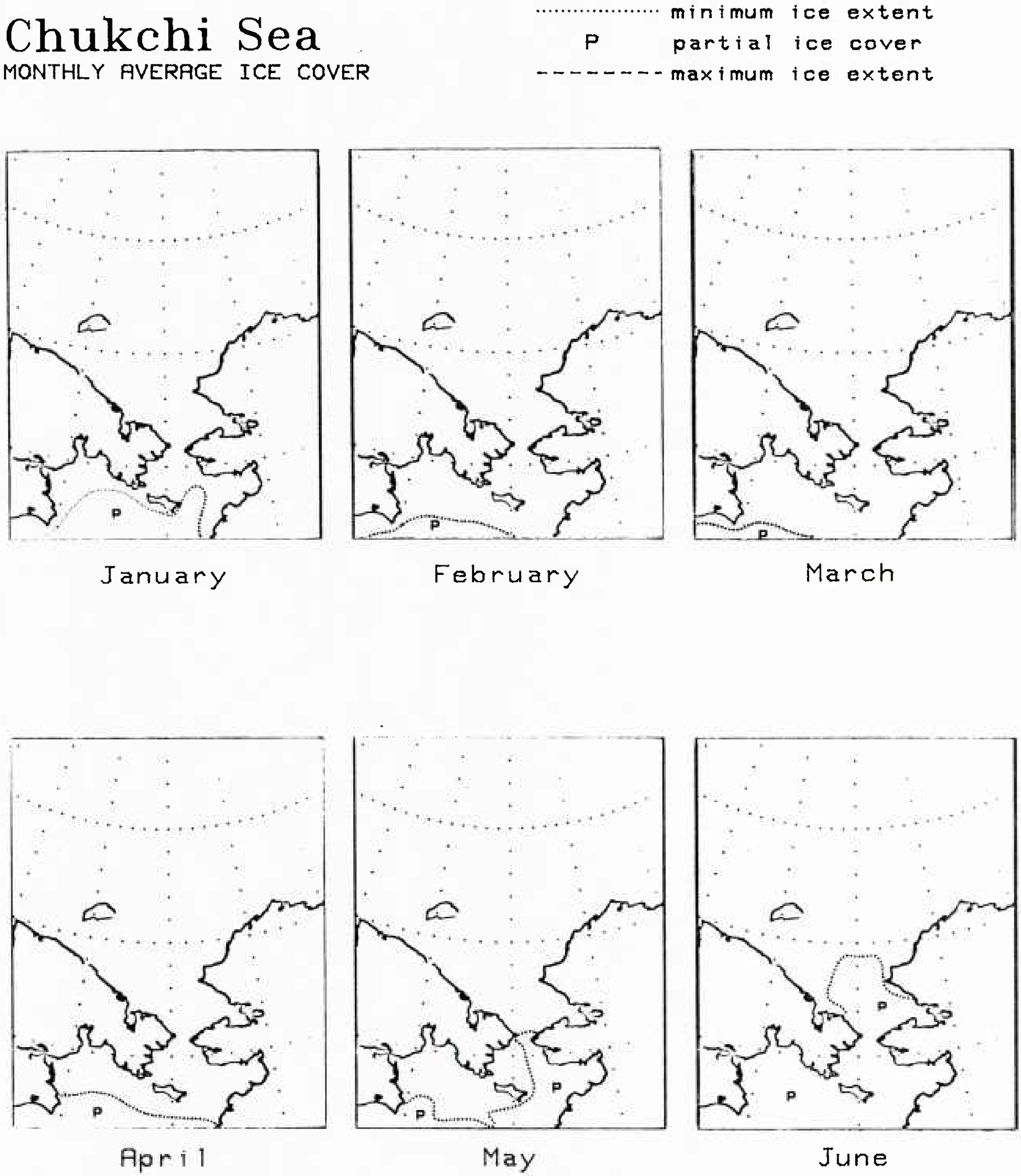
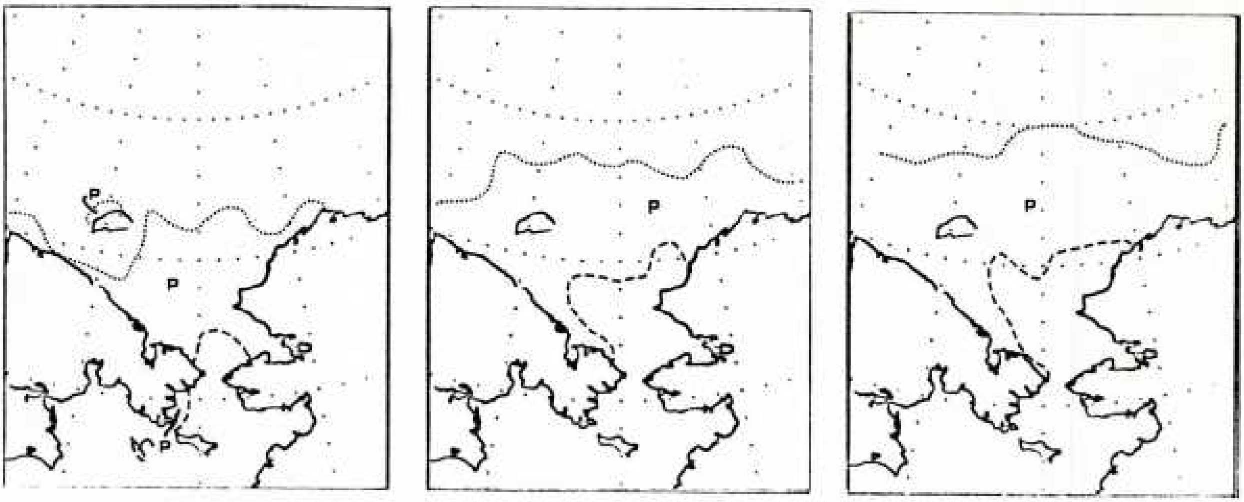
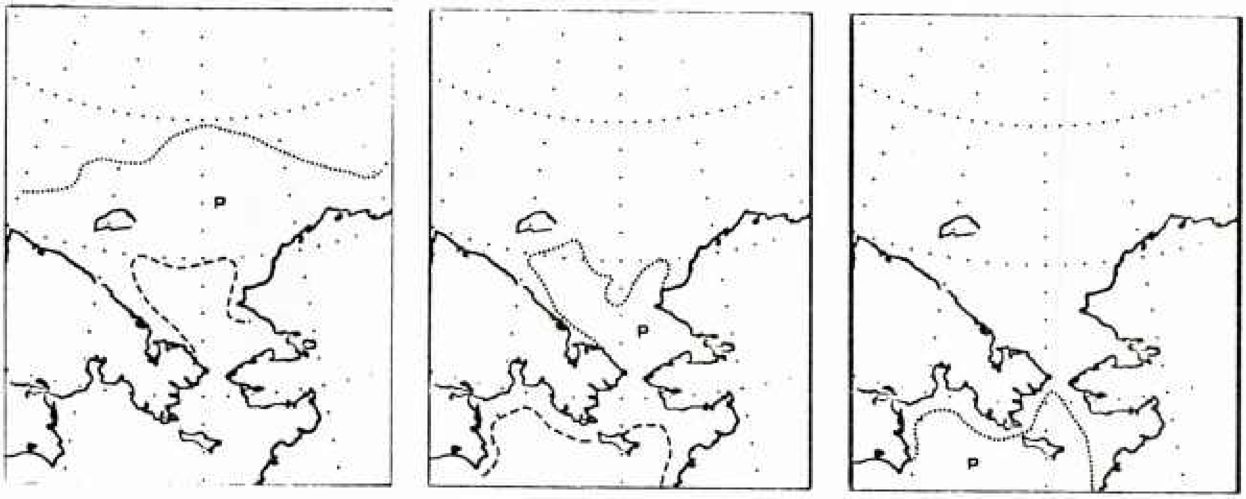


Figure C.1. Chukchi Sea monthly average ice cover.



July August September



October November December

Figure C.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix D: Kara Sea

Boundaries of the Kara Sea are
north—Franz Joseph Land to Severnaya Zemlya;
south and east—Severnaya Zemlya to USSR mainland;
west—Novaya Zemlya to East Franz Joseph Land.

Oceanography

The Kara Sea has an area of 8.83×10^5 km^2 and a volume of 1.04×10^5 km^3. The Kara Sea lies entirely on the continental shelf and is relatively shallow. The average depth is 118 m, and maximum depth is 620 m. Oceanographic characteristics show high seasonal variations due to the formation of sea ice. Approximately 1500 km^3 of fresh water enters the sea annually, primarily from the Ob and Yenisei Rivers. The fresh water, which sets up a northward current, diverges to the northeast along the coast of Taimyr and to the west and southwest along the coast of Novaya Zemlya, and establishes a counterclockwise eddy in the southwest. Surface salinities range from 7 to 20 ppt.

Atlantic waters of high density and salinity enter the sea from the Arctic Basin in the north and from the Barents Sea in the west flowing under the Arctic waters. In the northwest, these Atlantic waters occur even at the surface with a salinity of 32 to 34 ppt. In the summer, the less saline surface layer is 5°C to 8°C while the bottom water is 0 to -1.5°C.

Circulation

The predominant current in the Kara Sea forms a closed counterclockwise circulation in the western portion. The gyre begins in the east, and waters from the Ob and Yenisei Rivers spread as they leave the estuaries. One branch flows to Novaya Zemlya where it turns southwest to Proliv Karskiye Vorota. Within the main circulation are two small, weak, counterclockwise eddies. Water also enters the Kara Sea around the north of Novaya Zemlya from the Barents Sea and eventually mixes with the Ob and Yenisei waters. General circulation is shown in Figure 2.1 of the main text.

Sea ice

Ice conditions in the Kara Sea depend largely on the strength and direction of the prevailing winds. Most of the ice originates in the Kara Sea itself because currents and shallow water in the north act as barriers to the heavier pack ice of the Arctic Basin. Breakup advances from the south, where it is essentially open by July. Optimum navigation conditions are in August and September, but in good years they last from July to October. The worst conditions for navigation are usually encountered near Poluostrov Taimyr, where ice collects in the narrow straits and separates the islands of Arkhipelag Nordenshel'da and blocks the area immediately west of Proliv Vil'kitskogo. Conditions are quite variable elsewhere in the Kara Sea, but ice is apt to be heavy either in the northwest or in the southwest. Small icebergs may be found off northern Novaya Zemlya and Severnaya Zemlya. Mainland rivers begin to freeze in October at the river mouths, and at the same time fast ice develops around their mouths. Fast ice forms quickly and, anchored by the many islands, remains all winter. Along eastern Novaya Zemlya fast ice is 5 to 8 km wide, and north of the mainland it may exceed 25 km in width. The pack in the central Kara Sea is 1.5 to 3 m thick but considerably thicker where it is ridged or hummocked by pressure. Grounded hummocks, called ''Stamukhi,'' are common off Novaya Zemlya and Severnaya Zemlya. They reach heights of 9 m and tend to retain the surrounding ice cover in position. Ice conditions around Severnaya Zemlya are variable. The navigation season is usually from mid-August to mid-September. East of the archipelago there is ice all year, including some icebergs. East winds drive much of this ice between the islands making those straits impassable. Monthly average ice cover for the Kara Sea is shown in Figure D.1.

Detailed sea ice information can be found in *Ice Atlas of the Northern Sea Route (U)*, U.S. Naval Oceanographic Office, NSTL, Mississippi, N.O.P. 1202, February 1977. SECRET

Climatology

The climate of the Kara Sea is arctic, very similar to that of the adjacent Laptev Sea. Precipitation is generally less than 10 cm per year. The presence of some year-round sea ice prevents seas from exceeding 1.5 m except on rare occasions. Visibility is less than 2 km for about 130 days/year.

Temperatures

Winter	–29°C to –4°C
Summer	–12°C to 7°C

Range of mean daily temperatures is –29°C to 7°C.
Lowest recorded temperature is –48°C.
The temperature may be below –31.5°C 30 days/year.

Winds

Winter	6 to 8 m/sec SE to S
Summer	5 to 8 m/sec N to NE

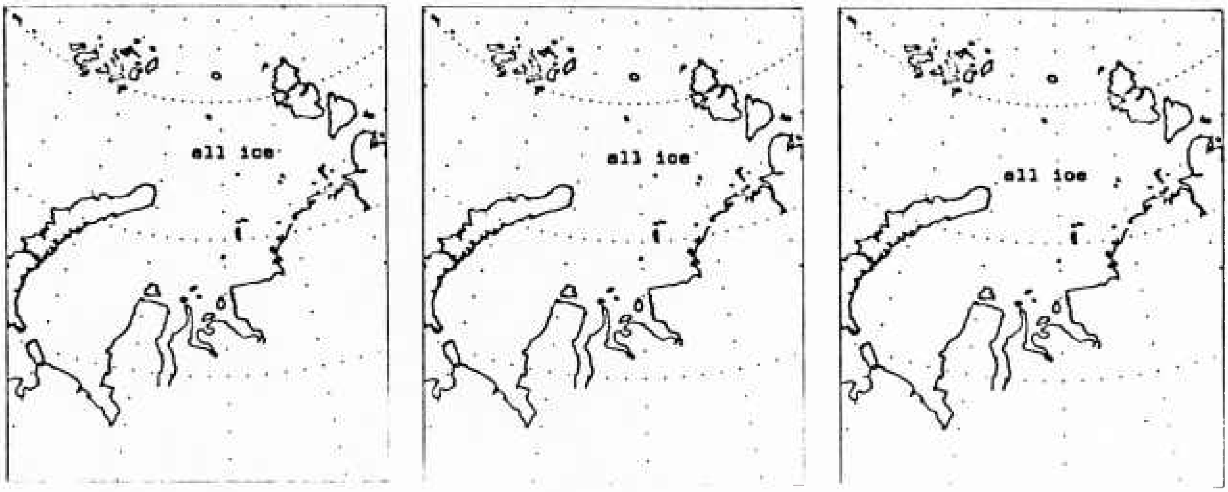
Winds may exceed 11 m/sec 70 days/year.

Sea state

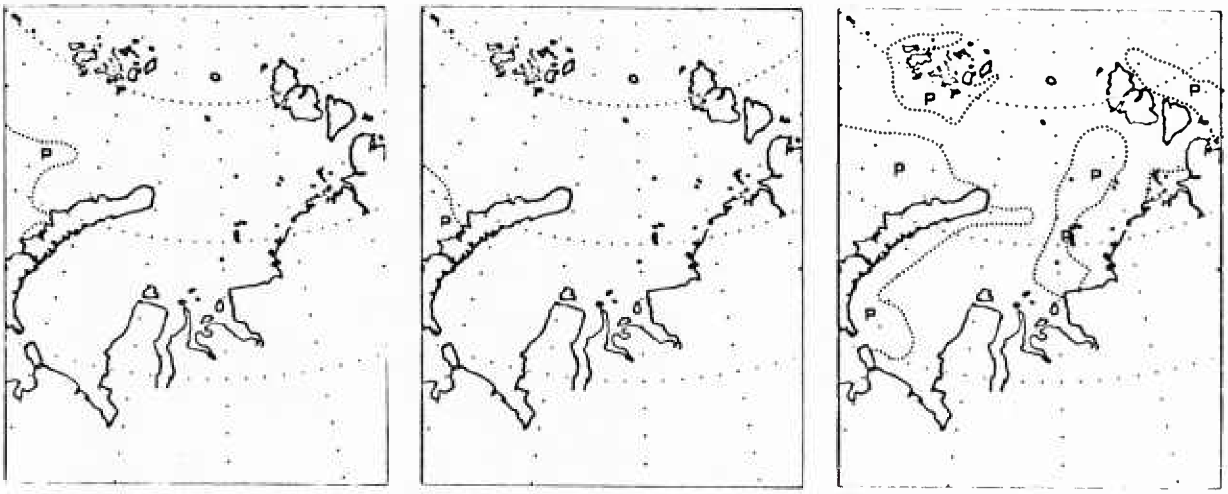
The near-constant presence of an ice cover and generally light winds prevent the occurrence of seas greater than 1 m.

Kara Sea
MONTHLY AVERAGE ICE COVER

·················· minimum ice extent
P partial ice cover
-------- maximum ice extent

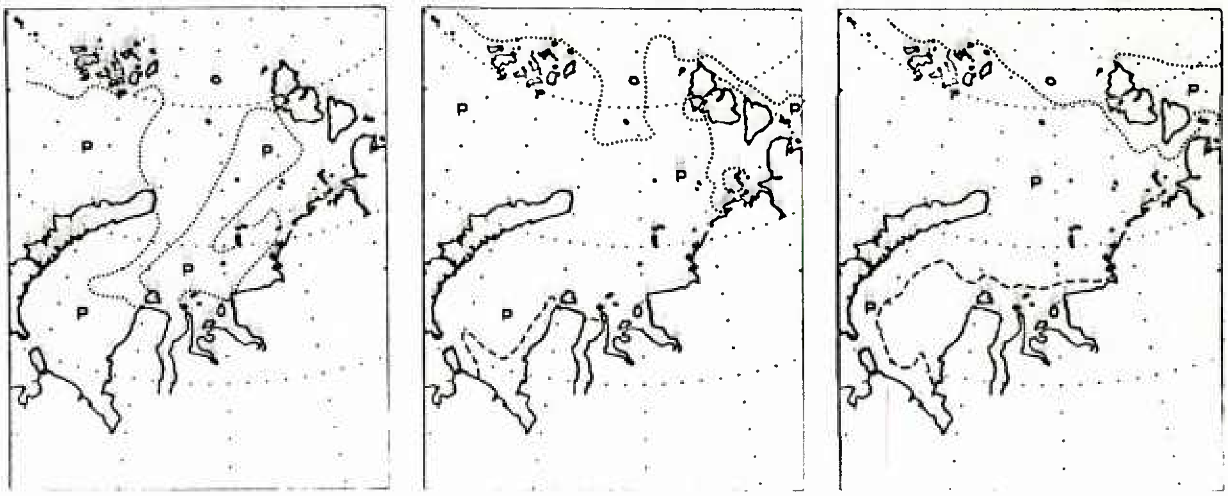


January February March

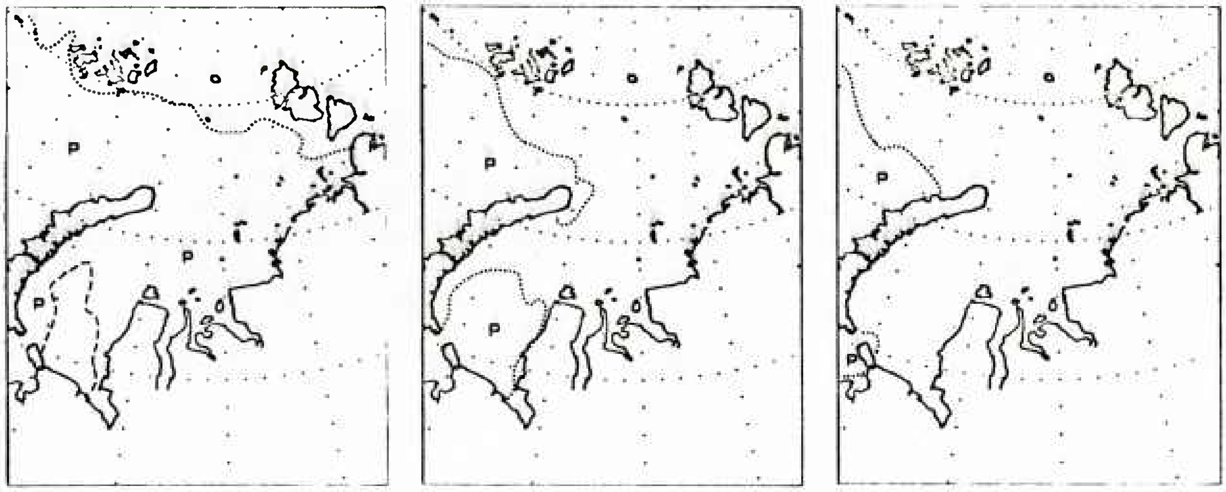


April May June

Figure D.1. Kara Sea monthly average ice cover.



July August September



October November December

Figure D.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix E: Greenland Sea

The boundaries of the Greenland Sea are

north—a line joining the northern limits of Greenland and Spitsbergen (Svalbard);

south—a line joining Straumners (northwest point of Iceland) to Cape Namen in Greenland (68°15′N, 29°30′W);

east—a line from the southernmost point of West Spitsbergen to Jan Mayen Island, and the eastern limit of Gerpir in Iceland;

west—Greenland.

Oceanography

The Greenland Sea has an area of 1.205 x 10^6 km^2 and a volume of 2.408 x 10^6 km^3. The mean depth is 1444 m and maximum depth is 4846 m in the large "Greenland Basin."

The two basins of the Greenland Sea contain a very nearly uniform deep water with a salinity of about 34.92 ppt and a temperature about −1°C. Seventy percent of the combined basins is below 550 m depth and is filled with Norwegian Sea Deep Water. The mixed water in the upper layers of the Greenland Sea is cooled in winter, but before it can freeze it reaches a higher density than that of water below it and so sinks to form the Deep Water. In the region of the Iceland-Jan Mayen and Mohn Ridges, Arctic Intermediate Water appears above the Norwegian Sea Deep Water and below the Arctic Water of the East Greenland Current system. Its core is at about 400 m depth, the temperature is between 0° and 2°C, and the salinity is between 34.8 and 35.0 ppt. It is formed by the cooling of Atlantic Water and mixing with the Deep Water and, to a lesser degree, Arctic Water. The Atlantic water, which appears above in the Denmark Strait, comes from the Irminger Current. This water is warm (>8°C) and saline (>35 ppt). Farther south in the Icelandic coastal area, vertical mixing of Atlantic Water and Arctic Water in winter results in a homogeneous water mass in the uppermost 150 to 350 m. This water has a temperature of 2°C to 3°C and a salinity of 34.85 to 34.90 ppt, and is called North Icelandic Winter Water.

Circulation

The primary current in the Greenland Sea is the East Greenland Current, which is a continuation of the slow drift of surface water across the Central Arctic. As the flow becomes concentrated off Greenland, its speed increases and reaches about 25 cm/sec in the surface layer. The speeds of the various currents are not well established. Evidence suggests that the wind causes frequent changes. Some estimates put the speeds of the Atlantic Current and East Greenland Current at 22–44 km/day. Locally, the East Greenland Current can reach very high speeds of about 150 cm/sec just south of the Denmark Strait.

The northeasterly winds also intensify the surface current. To the north of the Denmark Strait, the strong southward current of 10–20 cm/sec is obtained by dynamic calculations in deep layers from 200 to 600 m on the slope off the Greenland Shelf. Also, a northward current of almost the same speed is determined in the deep layers just to the east of the southerly current. Both currents are about 30–50 km wide. A cyclonic gyre is located north of Jan Mayen Island between the Greenland current and a branch of the Norwegian current flowing west of Spitsbergen. This gyre occupies almost the entire Greenland Basin. It is called the Greenland gyre and is distinguished from the southern Norwegian gyre. General circulation is shown in Figure 2.1.

Sea ice

The distribution of sea ice in the Greenland Sea is determined by the East Greenland Current and its two branches and, to a lesser extent, by the East Spitsbergen Current. Off East Greenland a belt of sea ice, which is located about 500 km wide north of Scoresby Sound (70°N) in late winter, is present the entire year. The ice coverage reaches maximum in April and covers the entire sea, and the ice may be sighted along the north coast of Iceland. In September the ice coverage becomes minimal, and the coast south of about 70–72°N becomes navigable for specially built ships.

The Greenland Sea characteristically contains a high proportion of old ice that originates in the Arctic Ocean, but is supplemented by locally formed ice. Icebergs, which calved from the glaciers along the east coast of Greenland, are also present.

Beginning in September the southern and southeastern margin of the pack ice expands southward, until by December or January, a tongue of pack ice has reached the southern tip of Greenland and has effectively blocked the east coast. The margin of the ice begins to withdraw in May by melting on the outer side, ice breakup by sea swell, and the development of inshore leads between the coast and the pack ice. Although in general it appears to have been less in the 20th century than in the previous three centuries, forecasting the quantity and the distribution of East Greenland ice is still not possible. Monthly average ice cover for the Greenland Sea is shown in Figure E.1.

For detailed sea ice information see *Physical Properties of the Ice Cover of the Greenland Sea*, U.S. Army Cold Regions Research and Engineering Lab., Hanover, New Hampshire, November 1982.

Climatology

The Greenland Sea consists of two sections with widely varying climatic conditions. The air mass in the northern part of the Greenland Sea is arctic, while the southern part is usually polar maritime. Precipitation reaches a maximum in December and a minimum in July at Jan Mayen and is less on the northern coast of Greenland. The predominant surface winds are north to east at Jan Mayen, south to southwest at Nord on the north Greenland coast, and north to northwest at Danmarkshaven on the east coast of Greenland. Visibility is less than 2 km for about 20 days/year in the north and 30 days/year in the south. Low clouds and recurring fog further restrict visibility throughout the region during the summer season.

Temperatures

Northern Sector

Winter	−32°C to −12°C
Summer	−7°C to 4.5°C

Range of mean daily temperatures is −32°C to 4.5°C.
Lowest recorded temperature is −51°C.
Temperature may be less than −31.5°C 52 days/year.

Southern sector

Winter	−17°C to −4°C
Summer	−12°C to 10°C

Range of mean daily temperatures is −17°C to 10°C.
Lowest recorded temperature is −34°C.
Temperature may be less than 31.5°C 25 days/year.

Winds

Northern sector

Winter	3.5 to 6 m/sec
Summer	2.7 to 4.5 m/sec

Winds may exceed 11 m/sec 26 days/year.

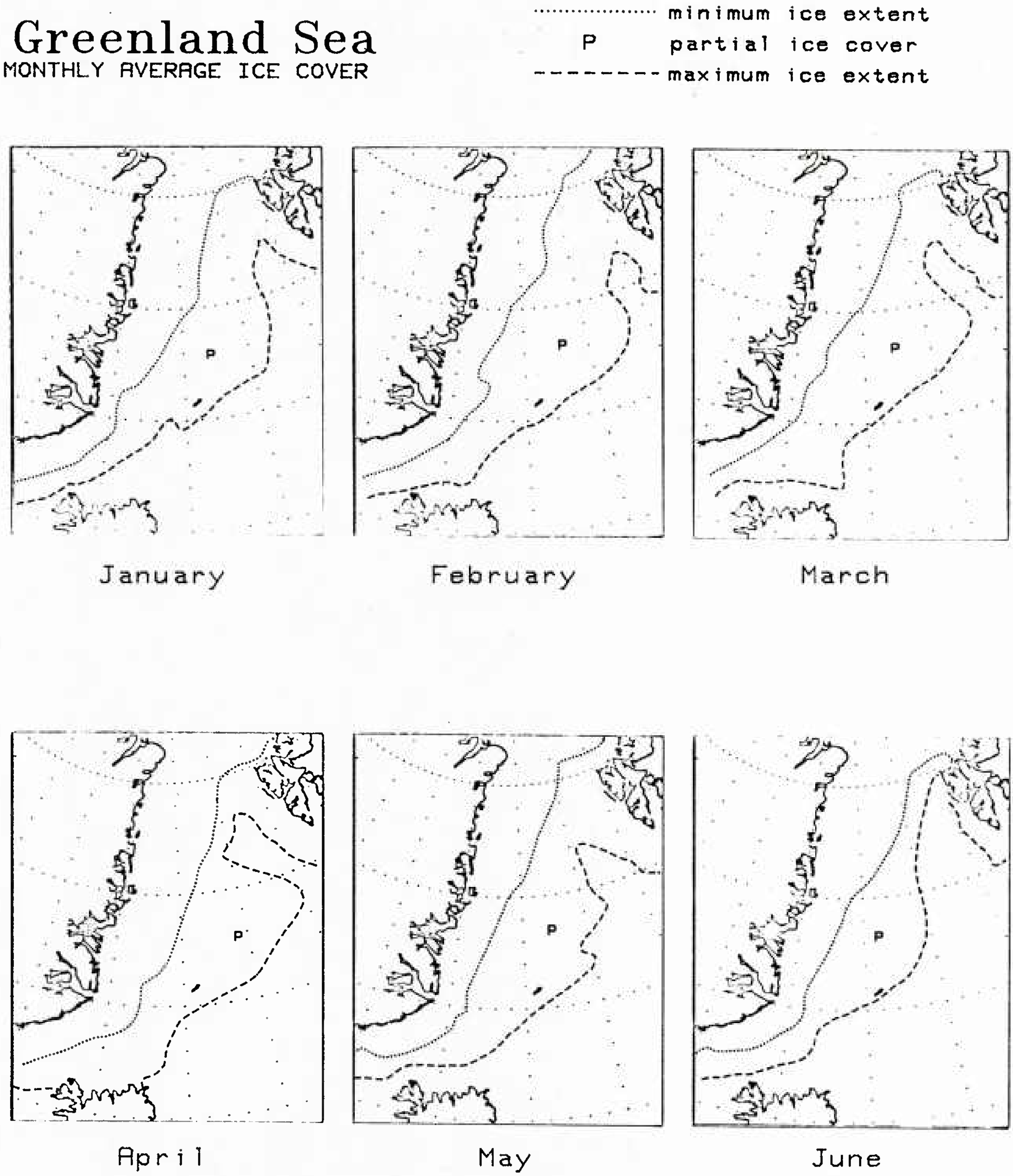
Southern sector

Winter	1.5 to 10 m/sec
Summer	1.5 to 8 m/sec

Winds may exceed 11 m/sec 74 days/year.

Sea state

Seas do not usually exceed 1.5 m in the Fram Strait but can be higher east toward Svalbard. The southern region is much more varied and seas often exceed 1.5 m.



January

February

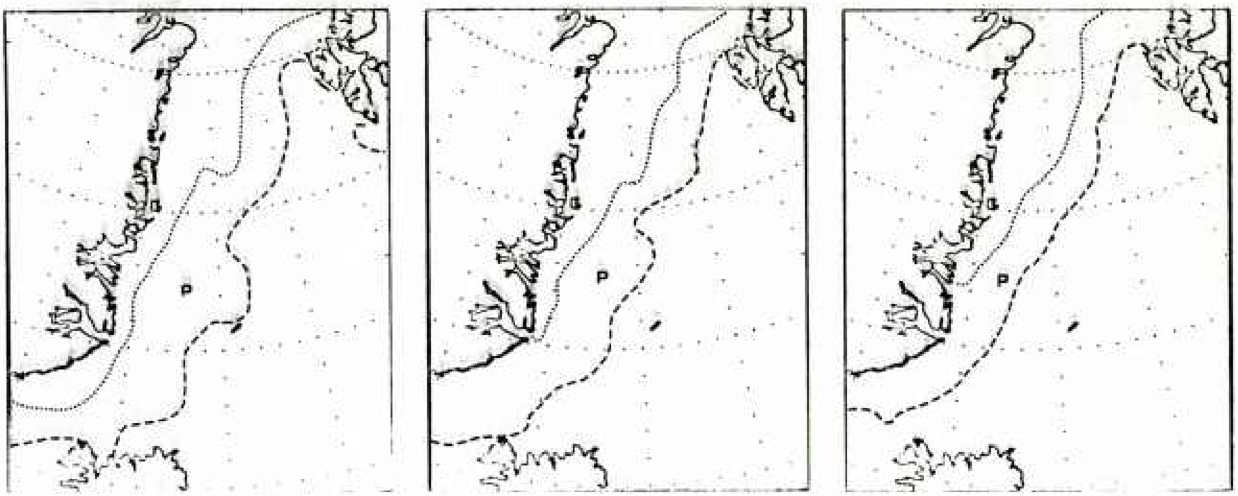
March

April

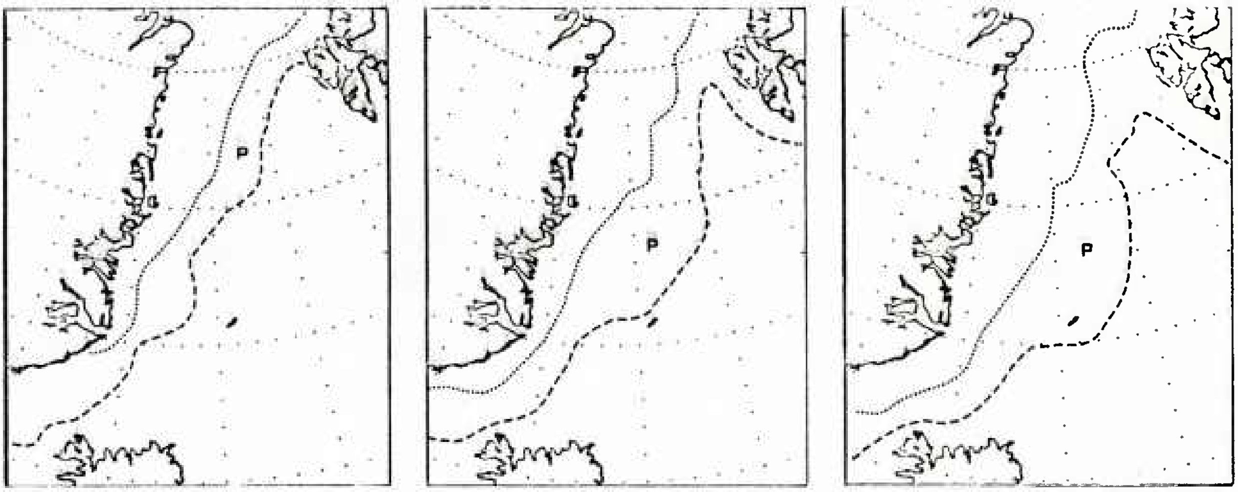
May

June

Figure E.1. Greenland Sea monthly average ice cover.



July   August   September



October   November   December

Figure E.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix F: Laptev Sea

Boundaries of the Laptev Sea are

north—rhumb line from the northern extremity of Severnaya Zemlya to the point where the meridian of 139°E crosses the shelf edge (150 km north of Kotel'nyy Island);

south—Siberia;

east—Kotel'nyy and Lyakhovskiye Islands;

west—Severnaya Zemlya.

Oceanography

The Laptev Sea has an area of 5.4×10^5 km^2, and 64% of the total area is less than 100 m deep. Due to the shallowness of the sea, the water characteristics undergo wide variations with season primarily due to the presence or absence of ice cover. In the summer of 1963 data obtained by the USCG icebreaker NORTHWIND showed that the temperature and salinity distribution had a high degree of stratification. Temperatures generally were observed to increase toward the Siberian Coast and vertically from the bottom. Salinities were observed to decrease toward the coast and vertically from the bottom. Below 20 m temperatures and salinities appear to be similar to surface water found in the Arctic Basin. Temperatures of 1.4°C to −1.8°C were observed and salinity values were greater than 28 ppt. In the upper 15 m, temperatures are even higher and salinities even lower.

Detailed oceanographic information collected in summer can be found in *Some Summer Oceanographic Features of the Laptev and East Siberian Seas*, U.S. Naval Oceanographic Office, NSTL, Mississippi, Technical Report 200, January 1968.

Circulation

The general flow of water in the Laptev Sea is counterclockwise. The major current entering the Laptev Sea comes through Proliv Vil'kitskogo between M. Chelyuskin and Severnaya Zemlya. It is joined by a cold current that flows southeastward along Severnaya Zemlya at 10 cm/sec, and the combined waters move along the Taymyr Coast into the shallow part of the Laptev Sea. At the Lena Delta the current splits. One part, which flows along the west side of the Novosibirskiye Ostrova at 30–60 cm/sec, sets to the north of the Archipelago and joins the main Arctic drift. The other part flows through Proliv Dmitriya Lapteva and Proliv Samnikova into the Eastern Siberian Sea. General circulation is shown in Figure 2.1.

Sea ice

The Laptev Sea is covered with sea ice for a large portion of the year, and the ice sometimes remains in the northern part over the entire summer. The ice drift direction depends on meteorologic conditions (atmospheric pressure). When there is a polar pressure maximum, an anticyclonic current circulation builds up in the sea, which favors ice drift from the Laptev Sea to the west. Ice in this sea usually forms rapidly as the temperature of this shallow sea changes rapidly in fall. Hummocky ice more than 10 m high is common at the boundary of the fast ice and pack ice, and is most strongly developed in the western Laptev Sea and in Proliv Longa. In the spring, ice melts first at the mouths of rivers and along the nearby coasts.

Ice on the smaller rivers melts in place, but on the large rivers violent ice movement, ice dams, and flooding occur. The navigation period for the lower reaches of the rivers is 3–4 months. Freeze-up begins at Tiksi, in Guba Buor Khaya, in early October and spreads east and west from there. By December the sea is completely frozen over. Ice conditions vary from the west to the east. In the west, wind causes much hummocky and rafted ice. Large fields of heavy sea ice are often located off Severnaya Zemlya and Taymyr, where heavy floes and icebergs may run aground as they are driven southward. In the eastern part, the ice is generally smoother and is 150–225 cm thick. The fast ice is 15–25 km wide off the northeastern parts of Taymyr, 80–100 km wide along the southern shores of the sea, and 400 km wide from the mainland to north of the Novosibirskiye Ostrova.

Break-up begins in June off the deltas of the Lena and Yana Rivers. The eastern side of the Laptev Sea is the first to be free of ice because of the influx of river water and the presence of winds blowing the ice off-shore. Changes in the western part are slower because of the deeper water and the cold current that flows south along the east coast of Severnaya Zemlya. Once the ice has broken up in the west, the ice margin retreats 15–40 km per day. The southern part of the Laptev Sea is navigable in July, but the seas on either side may not provide access. Heavy pack ice from the polar basin does not extend far into the Laptev Sea and only small quantities find their way south. The navigation season is effectively August and September.

Monthly average ice cover for the Laptev Sea is shown in Figure F.1.

Detailed sea ice information can be found in *Ice Atlas of the Northern Sea Route (U)*, U.S. Naval Oceanographic Office, NSTL, Mississippi, N.O.P. 1202, February 1977. SECRET

Climatology

The climate of the Laptev Sea is arctic. The precipitation is not more than 10 cm per year. The presence of year-round sea ice prevents seas from becoming greater than 1.5 m except on rare occasions. Visibility is less than 2 km for about 75 days/year largely due to fog in the summer and blowing snow during the winter months.

Temperatures

Winter	−34°C to −17°C
Summer	−12°C to 7°C

Range of mean daily temperatures is −34 to 7°C.
Lowest recorded temperature is −48°C.
Temperature may be less than −31.5°C 60 days/year.

Winds

Winter	4.5 to 6 m/sec
Summer	4.5 to 7 m/sec

Winds are variable in direction SE to NW.
Winds may exceed 11 m/sec 50 days/year.

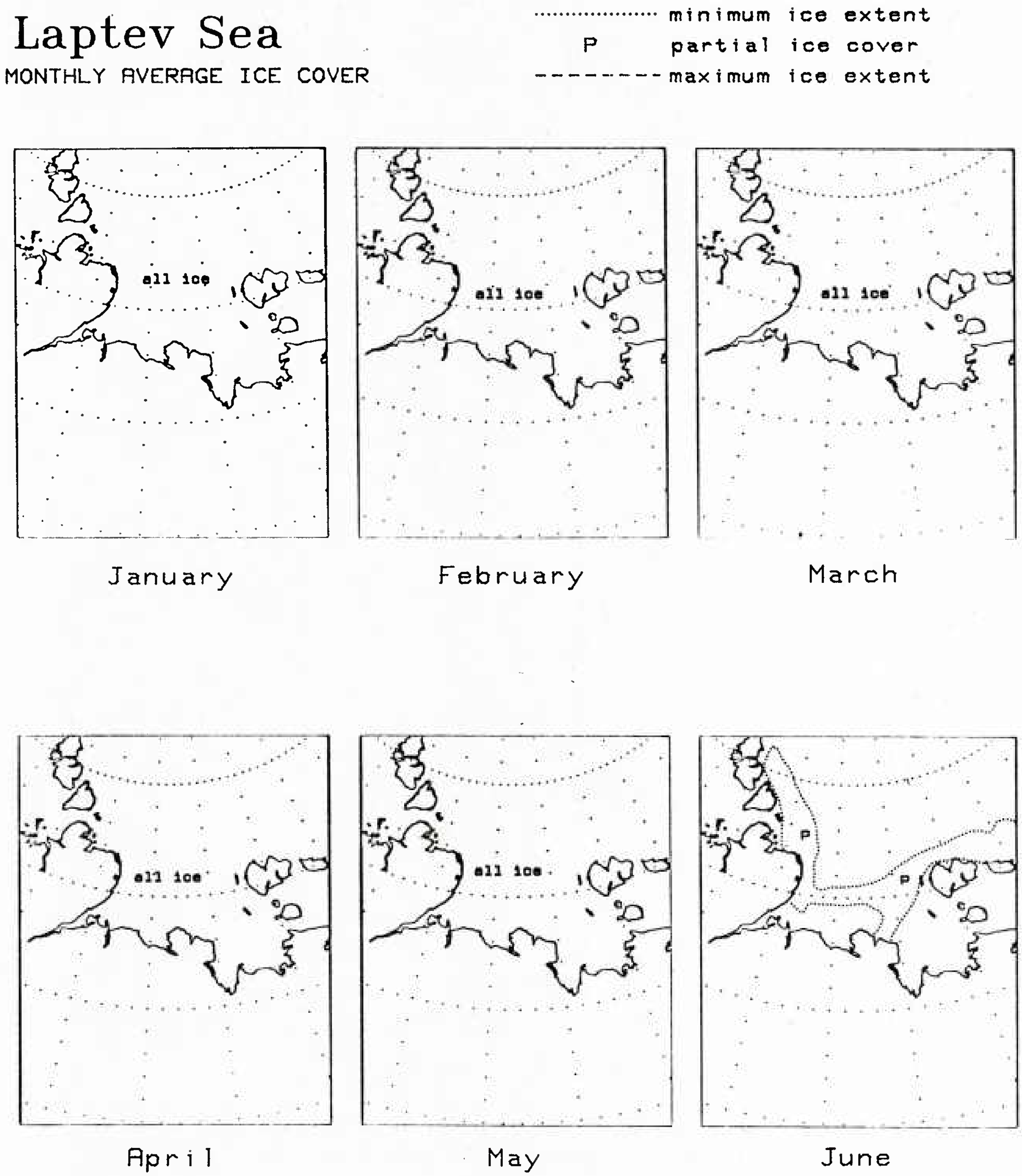
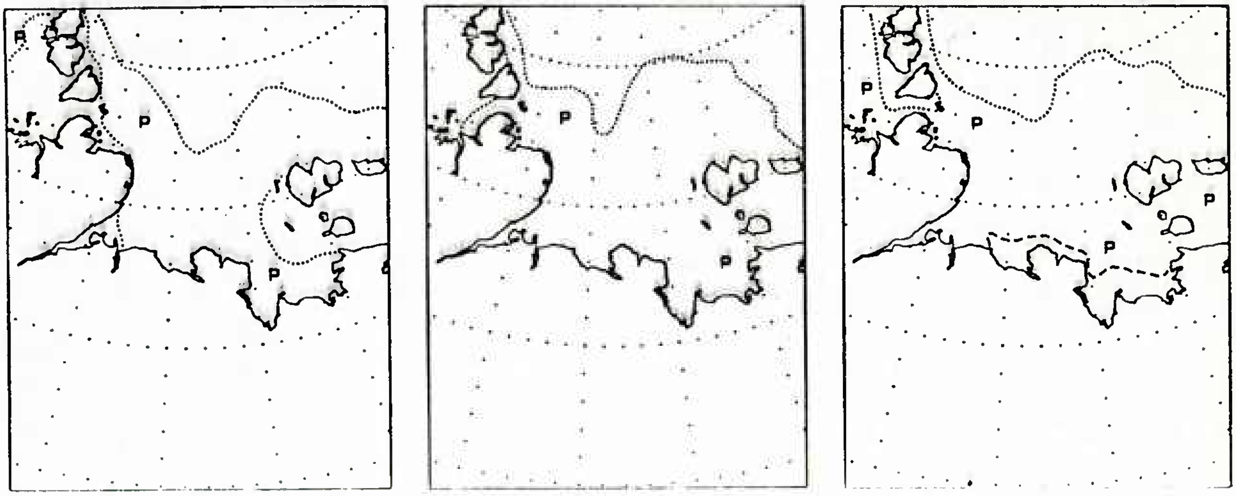
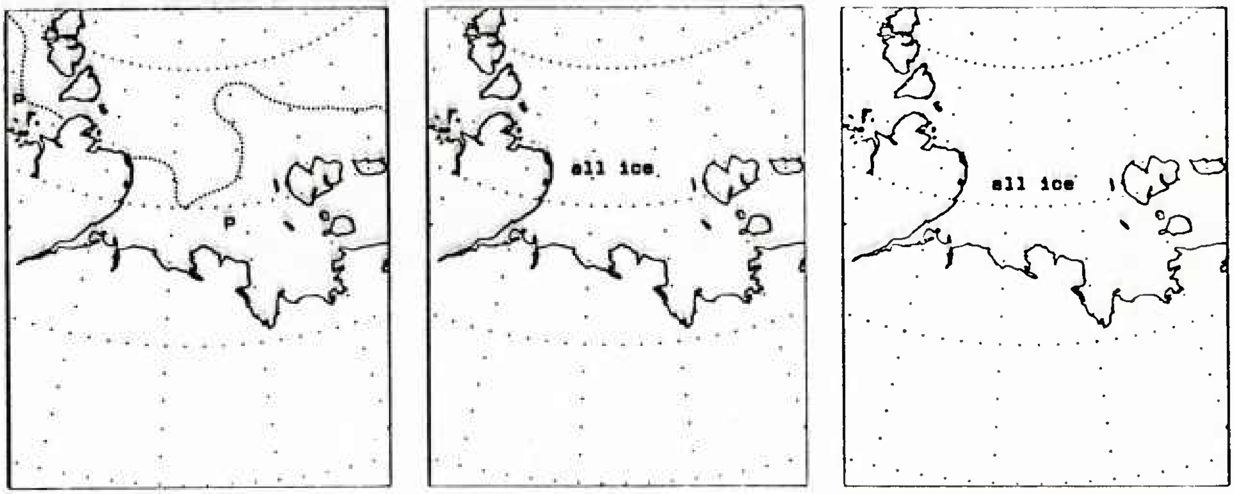


Figure F.1. Laptev Sea monthly average ice cover.



July August September



October November December

Figure F.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix G: Sea of Okhotsk

The boundaries of the Sea of Okhotsk are

north—U.S.S.R. with extreme point being the head of the Penjenskaya Guba (bay) (63°N, 164°E);

south and east—Japan, Kuril Island Chain, Kamchatka Peninsula;

west—U.S.S.R.

Oceanography

The sea of Okhotsk has an area of 1.58 x 10^6 km^2, a volume of 1.23 x 10^6 km^3, an average depth of 777 m, and a maximum depth of 3375 m.

The physical properties of the waters in the Sea of Okhotsk show great seasonal and regional variability because even in the mildest winters the formation, presence, and melting of ice play a major role in the horizontal and vertical structure of the waters of this semi-enclosed sea. In the winter the surface water cools and convective mixing takes place until all the water in the column to depths of approximately 200 m becomes isothermal, isohaline, and isopycnic and ice begins to form on the surface. These winter conditions occur initially in the northern part of the Sea of Okhotsk, abetted somewhat by the counterclockwise circulation of the cold, slightly more saline Oyashio water flowing in from around the southern tip of the Kamchatka Peninsula.

With the strengthening of the Siberian atmospheric high, the wind pattern and, thus, the current patterns change. Ice formed in the northern part of the Sea of Okhotsk is transported by the East Sakhalin Current into the comparatively warmer southern part of the sea. The southerly movement of the ice pack aids the cooling of the water in the southern part.

In addition, the changes in wind pattern sharply decrease the flow of warmer, more saline water through La Perouse Strait into the southern part of the Sea of Okhotsk. With the reduction of this flow and the southward pressure of the East Sakhalin Current, the waters north of Hokkaido are clogged with ice. The deep, cold surface layer conditions typical of the northern part of the Sea of Okhotsk earlier in winter now occur in the southern part as well.

With the advent of spring, the wind patterns change, which causes a weakening of the East Sakhalin Current and an increase in the eastward flow of water through La Perouse Strait. This increased warmer, more saline flow, together with increased solar radiation during the spring, causes a gradual deterioration and melting of the ice pack. The resultant low-salinity melt water accumulates and spreads out as a thin layer over the dense waters of the area. This layer of comparatively warm (0°C), low-salinity surface water is augmented by runoff, which peaks in late spring and summer. The thin, low-salinity layer remains until a spring storm mixes it into the colder winter water layer below, rapidly decreasing its thickness. This process continues in various degrees according to region and severity of the season. The maximum extent of the minimum temperature layer at a depth of 100 m occurs in the spring when the heat loss is slower. The surface layer temperatures, which cover the majority of the sea, range from −1.8°C to 0°C. At 50 and 100 m, the minimum salinity layer of cold water shows a characteristic salinity of 33.00 ppt to 33.25 ppt. Below this layer the salinity gradually increases and reaches a value of approximately 34.50 ppt at 1500 m.

Positive sound velocity gradients, which result from low sea surface temperatures, are characteristic of the sea. With increasing solar radiation in the spring, the development of a shallow thermocline is reflected in the sound velocity structure by a weak near-surface sound channel. This shallow near-surface sound channel attains its maximum development in summer.

Detailed water properties, circulation, sea ice, acoustics, and environmental parameters of the Sea of Okhotsk can be found in *Environmental Guide NP-4, Sea of Okhotsk (U)*, U.S. Naval Oceanographic Office, NSTL, Mississippi, SP3160-NP4, 1982. SECRET

Circulation

Water enters from the Sea of Japan through La Perouse Strait and through several Kuril Islands straits. Surface currents have counterclockwise direction at speeds of 2–10 cm/sec. Water entering through La Perouse Strait produces the strong (50–90 cm/sec) near-shore Soya Current.

The general circulation in the Sea of Okhotsk is counterclockwise and runs strongest 30–65 km offshore.

A complex pattern of currents has been reported from the middle of the sea. The current moves north along western Kamchatka at 25 cm/sec (0.5 knot); in other sectors velocities up to 50 cm/sec (1 knot) are recorded. The Sea of Okhotsk has one unusual feature that affects both the ice conditions and the climate. This consists of patches of substantially colder waters that are located at the entrance of Guba Shelekhova and Ostrava Iony and between the Cstrov Shanta and northern Sakhalin. These cold spots mark upwellings of colder, deeper water, and the cause is still unknown. They are associated with continuous dense fogs in the summer and with concentration of ice in the winter. The exchange of water with the Pacific Ocean is not great due to the shallow depths (usually less than 500 m) of the channels between the Kuril Islands. Pacific waters normally enter through the northeastern channels, and Okhotsk water leaves by the southwestern channels.

Sea ice

Glacier ice is not found in the Sea of Okhotsk. The dominant sea ice type is first-year ice with smaller concentrations of new and young ice types. The sea ice is drifting and concentrations are changing constantly. Changes in oceanographic and meteorological conditions may cause drastic variations in both short- and longterm ice conditions. In mild ice seasons the center of the Sea of Okhotsk may be relatively ice free, with little drifting ice reaching the coast of Hokkaido. During severe ice seasons, however, most of the Sea of Okhotsk will have a high concentration of ice, with hummocks occurring over the entire region. The average maximum thickness of ice attained by locally formed sea ice in March and early April is about 1.3 m. Tidal flooding, splashing, and other factors may increase the total thickness to about 2.3 m in severe ice seasons.

Ice fracturing, rafting, and ridging occur throughout the area and are accompanied by noise that can be detected over a wide range of frequencies. The largest pressure ridges and hummocks occur near the coasts and may extend as high as 9 m. As the winds push the ice back and forth, many openings occur in the ice cover. Open water is always present because of the drift in the ice-covered parts of the sea. The leads and polynyas may quickly close in one area, but other openings form elsewhere.

Ice conditions in the Sea of Okhotsk closely resemble those in Hudson Bay. Ice usually forms in the northern bays in late October or early November. It covers the bay completely by December, and by this time there is floating ice throughout the northern half of the sea. Ice continues to form under the influence of the intensely cold continental air mass until April, and the strong winds carry it toward the Kuril Islands until the whole sea is covered. Drift ice is present in the Kuril Straits from January until March; the amount depends on the strength and duration of the winter monsoon. Sometimes the ice moves well into the Pacific before melting completely. In the north the breakup comes in May, starting with the river meltwater, which forces the landfast ice out to sea. The Shantar Islands are sometimes blocked until July, but the sea is generally ice-free in June. Monthly average ice cover for the Sea of Okhotsk is shown in Figure G.1.

Climatology

The east-facing geographical position of the Sea of Okhotsk is similar to that of China in the monsoon climate zone of the midlatitudes. Ranging from 45 to 60°N and extending into the Asiatic continent with its extremely cold and long winter, the climate differs little from the climate of the polar seas, especially in the northern part. From October to April, the winter monsoon produces north and northwest winds, which often reach storm force. The summer monsoon, which has prevailing southeast winds that often alternate with calms, begins in May and lasts until September. The annual precipitation in the north is 23–30 cm (highest during November to February), but in the south it is 80–100 cm (highest during December to February) due to the influence of dry continental air in the northwest and wet maritime air in the south. Visibility of less than 2 km can be expected for about 20 days/year in the north and 60 days/year in the south. Dense fog is frequent in the extreme southern portion.

Temperatures

Winter	−23°C to −7°C
Summer	−1°C to 16°C

Range of mean daily temperatures is −23°C to 16°C.
Lowest recorded temperature is −46°C.

Winds

Winter	5 to 8 m/sec NW to N
Summer	1 to 3 m/sec W to SW

Average winds may exceed 11 m/sec 73 days/year.

Sea state

Seas in excess of 1.5 m occur 20–70% of the time in winter, and decrease in frequency of occurrence from south to north due to the growth and expansion of the sea ice cover. They can be expected 30–40% of the time throughout the Sea of Okhotsk during the summer.

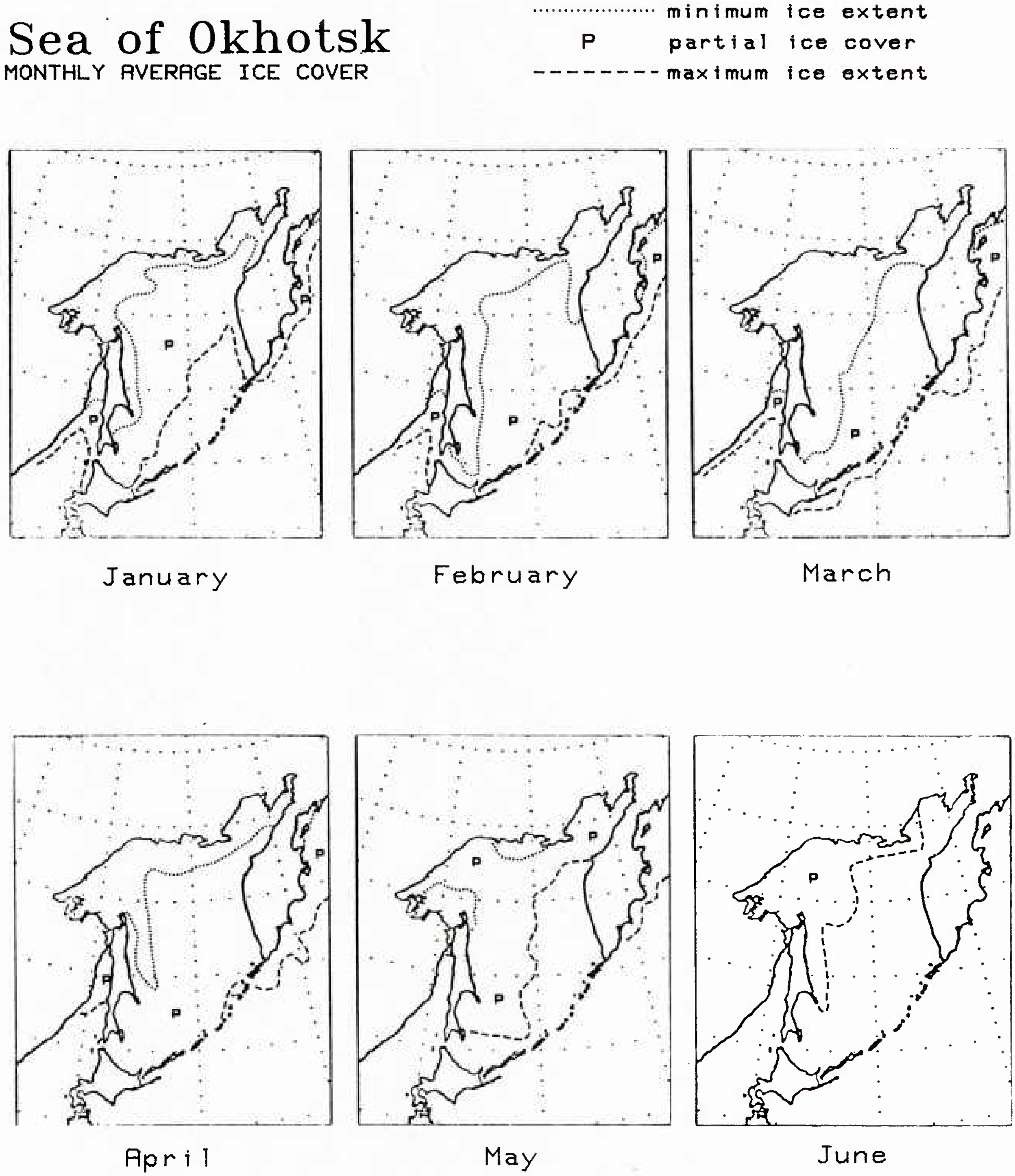
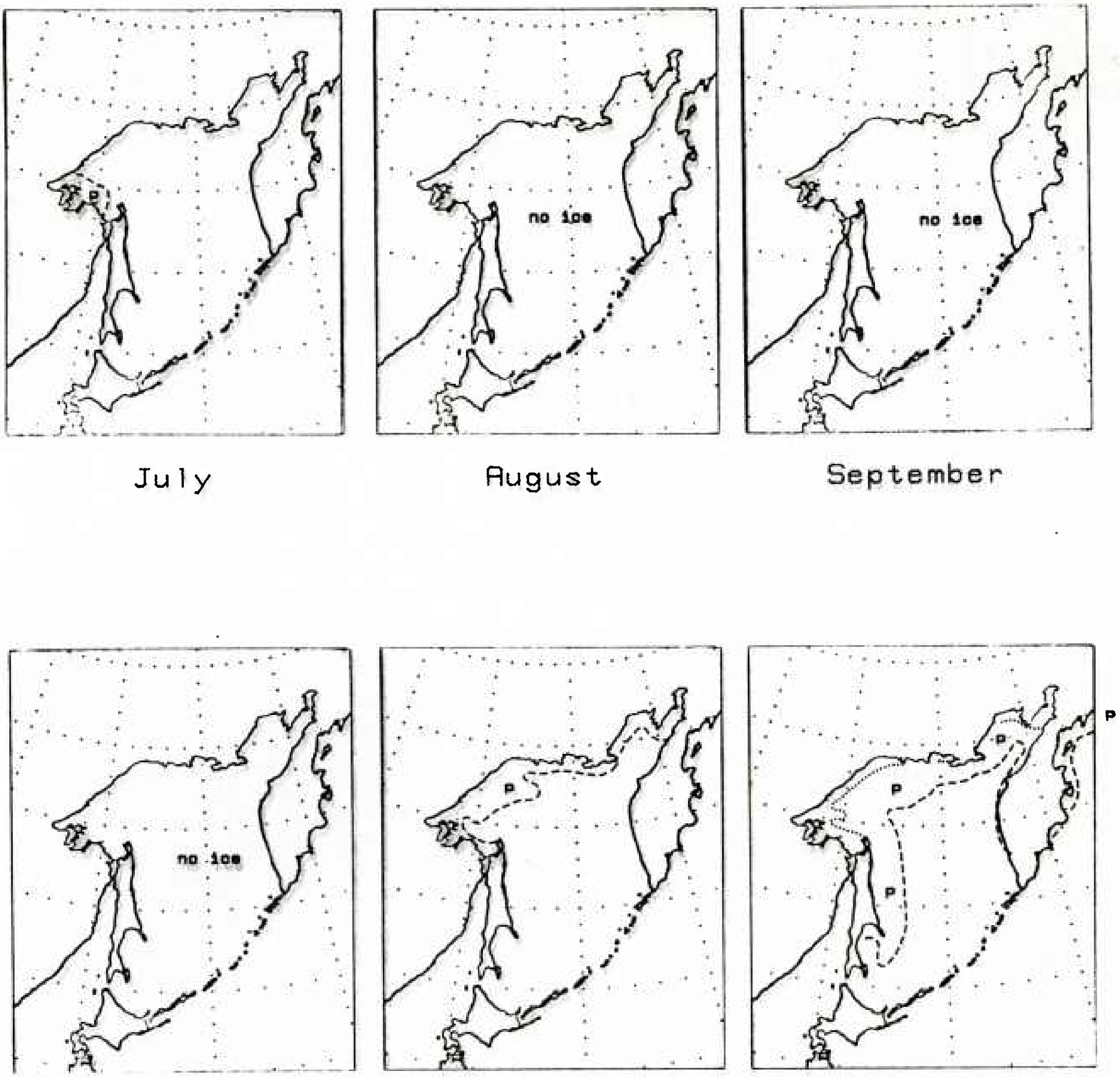


Figure G.1. Sea of Okhotsk monthly average ice cover.



July

August

September

October

November

December

Figure G.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix H: East Siberian Sea

Boundaries of the East Siberian Sea are

north—the 200-m contour located about 79ºN in the northwest (139ºE) and 76ºN in the east (180ºE);

south—Siberia;

west—coast of Kotelny and Lyakhovskiye Islands;

east—approximately the meridian of 180ºE.

Oceanography

The area of the sea within these boundaries is 6.6 x 10^5 km^2. The prevailing depths in this shallow marginal sea in the western and central parts are 10–20 m, and those in the eastern part are 30–40 m. Water characteristics of the East Siberian Sea, as with the Laptev Sea, vary greatly with ice conditions and river runoff. The eastern part of the sea is usually characterized by greater salinity and lower water temperature as compared with the western part. The highest water temperature (6ºC to 7ºC) is observed in August near the mouths of big rivers when south winds are blowing. Salinity ranges from 10 to 15 ppt and increases to 30 ppt near the ice edge. Water temperature near the ice edge decreases from 1ºC to – 2ºC. The water temperature, even off the coast, does not exceed 2ºC when north winds are blowing. In summer, a high degree of stratification forms, and temperatures increase vertically from the bottom and toward the coast. Salinities tend to decrease vertically from the bottom toward the coast.

Detailed summer oceanographic data can be found in *Some Summer Oceanographic Features of the Laptev and East Siberian Seas*, U.S. Naval Oceanographic Office, NSTL, Mississippi, Technical Report 200, January 1968.

Circulation

The flow in the East Siberian Sea is generally counterclockwise, as shown in Figure 2.1 of the main text. A weak easterly coastal current is modified by water from the large rivers, which forces it offshore in a northeasterly direction at 2 km/h; counterclockwise eddies develop when it is caught in coastal indentations.

The waters that pass through the straits, which separate Ostrova Novosibirskiye and the mainland, spread out upon reaching the East Siberian Sea. The main branch near the coast flows at approximately 0.5 to 2 km/h. A branch of this current is believed to pass north and west of Ostrov Vrangelya. In summer a current reaches through the Bering Strait and flows northwestward to the middle of Proliv Longa; its direction may be reversed in the winter.

North of the coastal currents in both the Laptev and the East Siberian Seas, the water flows in large counterclockwise eddies.

Sea ice

The East Siberian Sea is usually ice covered. In addition to a heavy ice cover, small icebergs calved from nearby islands are often present. When the polar anticyclone weakens, the area of cyclonic water circulation widens, which hinders the outflow of ice from the East Siberian Sea and favors the inflow of pack ice to the sea from high latitudes and ice blocking of the De Long Strait.

The first open water appears in late June off the Kolyma Delta. Open water expands rapidly west of the Kolyma and the ice edge moves to the north. In the eastern sector of the sea, the ice does not begin to clear for 1–2 weeks longer. The navigation season is 8–10 weeks in the west and 6–8 weeks in the east. During this period, ice conditions in the western sector are usually favorable for navigation. The heavy pack of the polar basin approaches the coast more frequently in the eastern section than anywhere else along the entire north Siberian shore. However, during the late summer, an open lead up to 30 km wide is usually close to the shore.

Freeze-up begins in the west and by late November an unbroken surface may extend 300–580 km offshore in the west, and narrow to 15–30 km off Mys Shmidta. Ice is constantly on the move in Proliv Longa. Monthly average ice cover for the East Siberian Sea is shown in Figure H.1.

Detailed Sea ice information can be found in *Ice Atlas of the Northern Sea Route (U)*, U.S. Naval Oceanographic Office, NSTL, Mississippi, N.O.P. 1202, February 1977. SECRET

Climatology

The East Siberian sea region has an arctic climate; January and February are the coldest and July is the warmest. In July and August easterly and northeasterly winds predominate, while in autumn, westerly and southwesterly winds blow near the coast. Northwesterlies have velocities of 20–25 m/sec and can generate 4–5 m waves. Visibility is restricted to less than 2 km for approximately 90 days/year.

Temperatures

Winter	– 37°C to – 15°C
Summer	– 12°C to 7°C

Range of mean temperatures is – 37°C to 7°C.
Lowest recorded temperature is – 48°C.
Temperatures may be less than – 31.5°C 38 days/year.

Winds

Winter	4.5 to 7 m/sec
Summer	4.5 to 8 m/sec

Winds may exceed 11 m/sec 23 days/year.

Sea state

Due to the almost continuous presence of an ice cover, seas rarely exceed 1 m. However, the occurrence of strong northwesterlies and a reduced ice cover during late summer can produce 4- to 5-m seas.

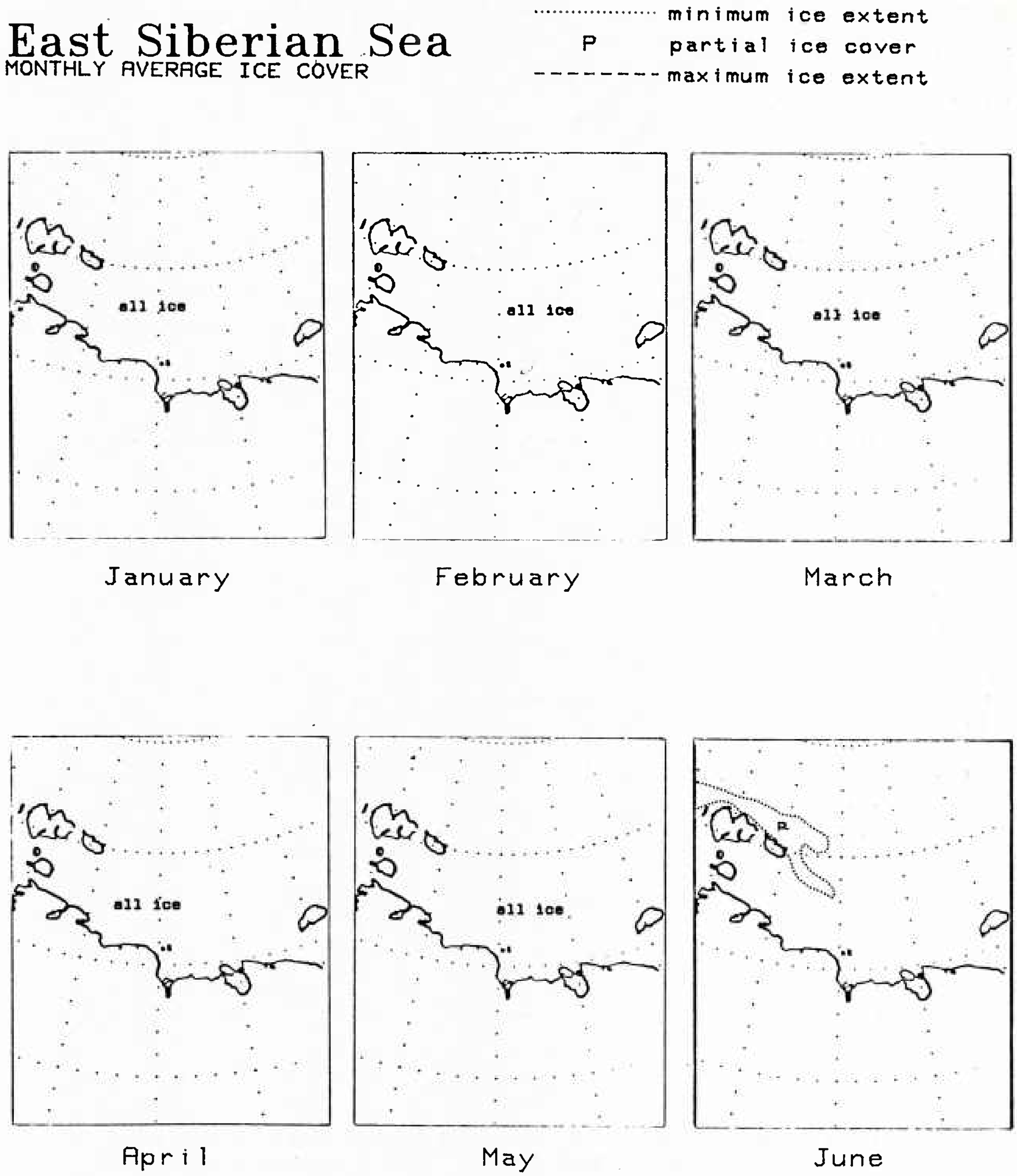
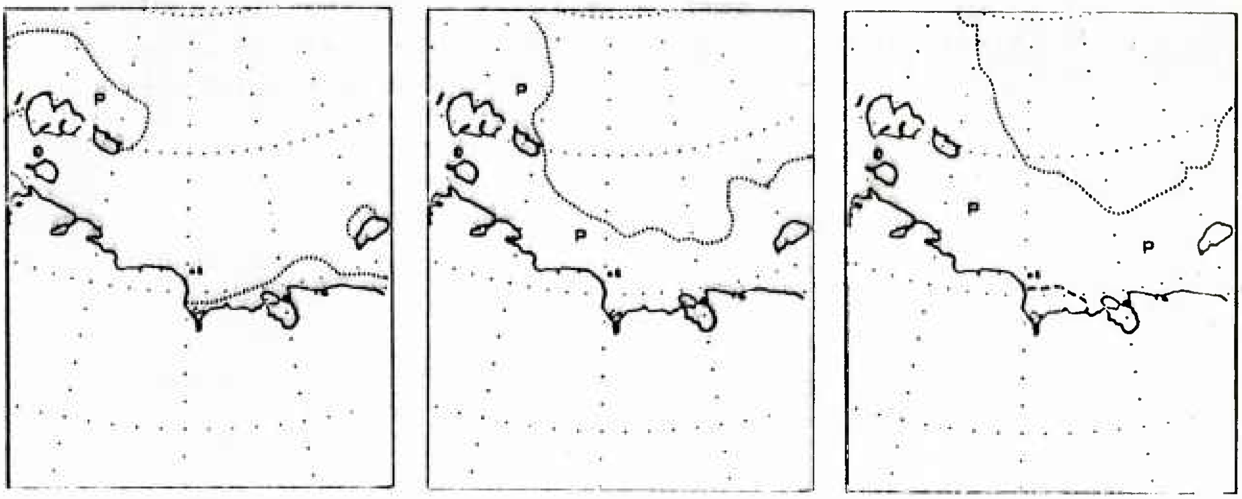
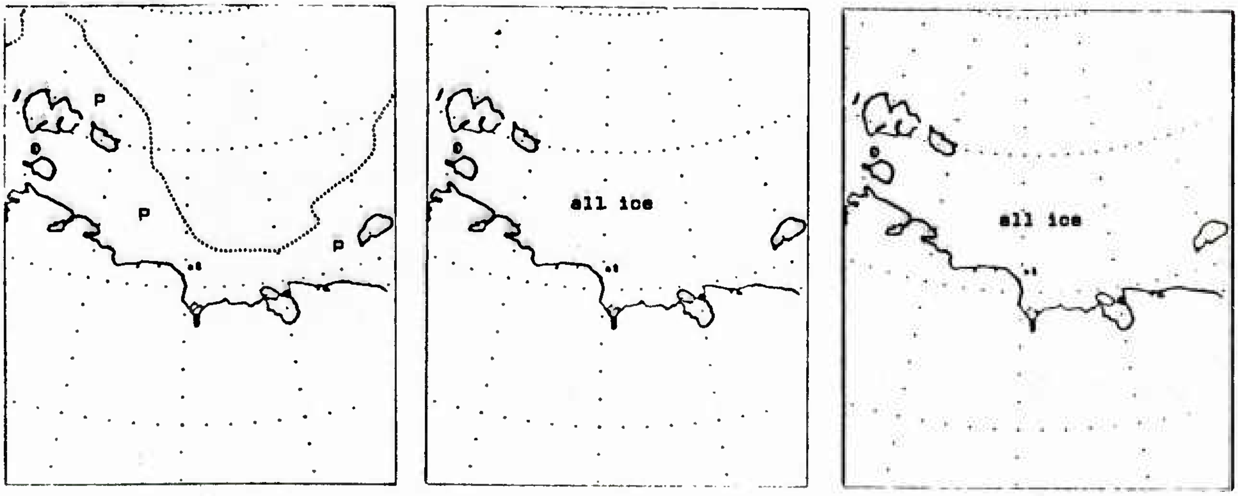


Figure H.1. East Siberian Sea monthly average ice cover.



July August September



October November December

Figure H.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix I: Labrador Sea

Boundaries of the Labrador Sea are

north—parallel 66°N across Davis Strait joining Greenland and Baffin Island;

south—a line from Cape Farvel, Greenland, to Cape St. Charles at the northern side of Belle Isle Strait;

east—Greenland;

west—coast of Labrador and the southeastern coast of Baffin Island.

Oceanography

The bulk of the waters in the Labrador Sea have a salinity around 34.9 ppt; highest values are found near the bottom. Average water temperatures are 2°–3.5°C; the lowest values are near the bottom. The waters from the central portion of the Labrador Sea are formed by the mixing of Atlantic water and Arctic water, which come partly from the East Greenland Current and partly from Baffin Bay. This mixed water is highly uniform, and salinities are between 34.88 and 34.94 ppt. As the surface water is cooled in winter, its density increases and it sinks to a depth proportional to the change. The deep and bottom water, formed by sinking of the surface water, flows south into the Atlantic and can be traced almost to the Antarctic Ocean. The average outflow of water from the Labrador Sea is estimated at 2 million m^3/sec.

The low-salinity (31–34 ppt) coastal water forms a narrow belt on the Greenland continental shelf. Its temperature shows high annual variation from 5°C to 6°C in summer to freezing point in winter. The East Greenland Current transports in water with high salinity (35 ppt) and has a temperature of about 5°C at depths below 150–200 m. The water on the Labrador Continental Shelf has a low salinity (30–34 ppt) and is colder than the Greenland coastal water; temperatures are below −1°C at a depth of 100 m, even in midsummer.

Circulation

The Labrador Sea has two major currents: the West Greenland Current and the Labrador Current, as shown in Figure 2.1 of the main text. The West Greenland Current, which flows northward along the coast of Greenland, transports a mixture of water from the East Greenland Current and the Atlantic. The Labrador Current flows southward off Baffin Island and Labrador and carries cold, low saline water from Baffin Bay and sounds of Baffin Island. Part of the East Greenland Current joins the Labrador Current south of Davis Strait.

Sea ice

The Labrador Sea is not completely ice covered in winter. The ice found there is of three types: locally frozen ice, pack ice from Baffin Bay, and icebergs that calve from Western Greenland and follow the Labrador Current southward. Because of the threat to shipping, these icebergs are of major concern in the Labrador Sea. Most of the eastern one-third of the sea is ice free all year, except for a region around the coast of southwest Greenland. The coast is open from August to December. The ice starts to form around Cape Farvel and spreads north in December. It attains its greatest northern extent in April–May when the coast is closed from Cape Farvel to about 62°N. Between this latitude and the Arctic Circle the outer coastline is always ice free, but fjords are frozen. The Canadian side is generally ice free until late September. Beginning in October, the ice belt off this side increases in width from the north. By the end of December, it extends to the southern limit of the Labrador Sea. In April/May it covers the western two-thirds of the sea, but in June to August it gradually disappears. Monthly average ice cover for the Labrador Sea is shown in Figure I.1.

Climatology

The climate of the Labrador Sea is of the polar and continental types to near 55°N on the Canadian side, and is of the maritime type on the Greenland side. Annual mean air temperature is about 5°–7°C higher on the Greenland side than on the Canadian side due to the influence of the warm Atlantic water. The precipitation also exhibits such differences in climatology between the west side and the east side of the Labrador Sea. The annual precipitation to the south of Cape Farvel (east side) reaches about 1 m, but it is less than 25 cm north of 55°N on the Canadian side, which represents the dry polar climate. Visibility is often poor throughout the year, less than 2 km for about 180 days.

Temperatures

Winter	$-12^{\circ}C$ to $-1^{\circ}C$
Summer	$-1^{\circ}C$ to $10^{\circ}C$

Lowest recorded temperature is $-29^{\circ}C$.

Winds

Winter	1 to 5 m/sec
Summer	1 to 5 m/sec

Winds are variable in direction, strong cyclones move rapidly across the Labrador Sea from west to east.

Sea state

Seas are moderated along the Labrador coast in winter by the presence of sea ice. However, they often exceed 1.5 m throughout the area.

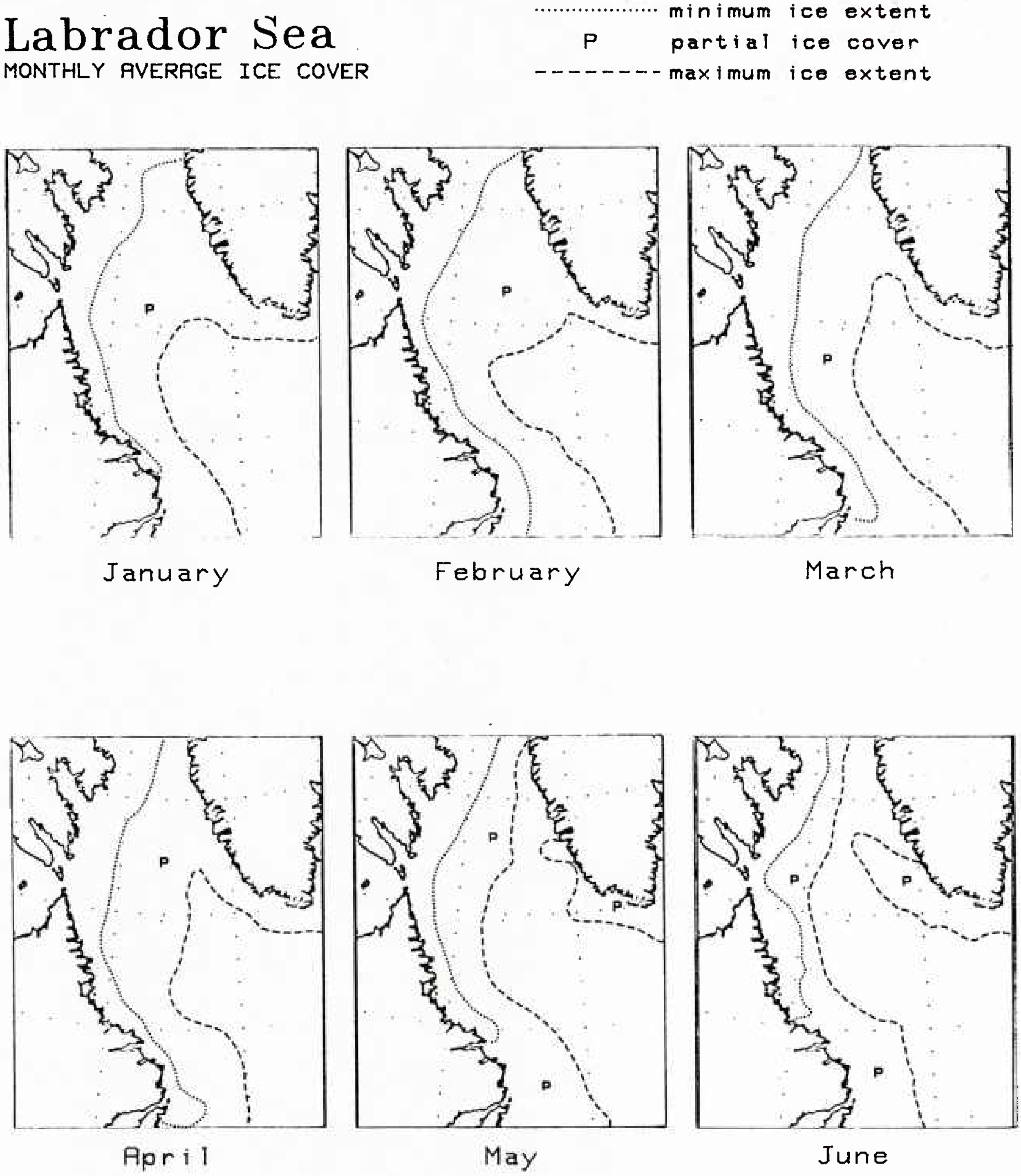
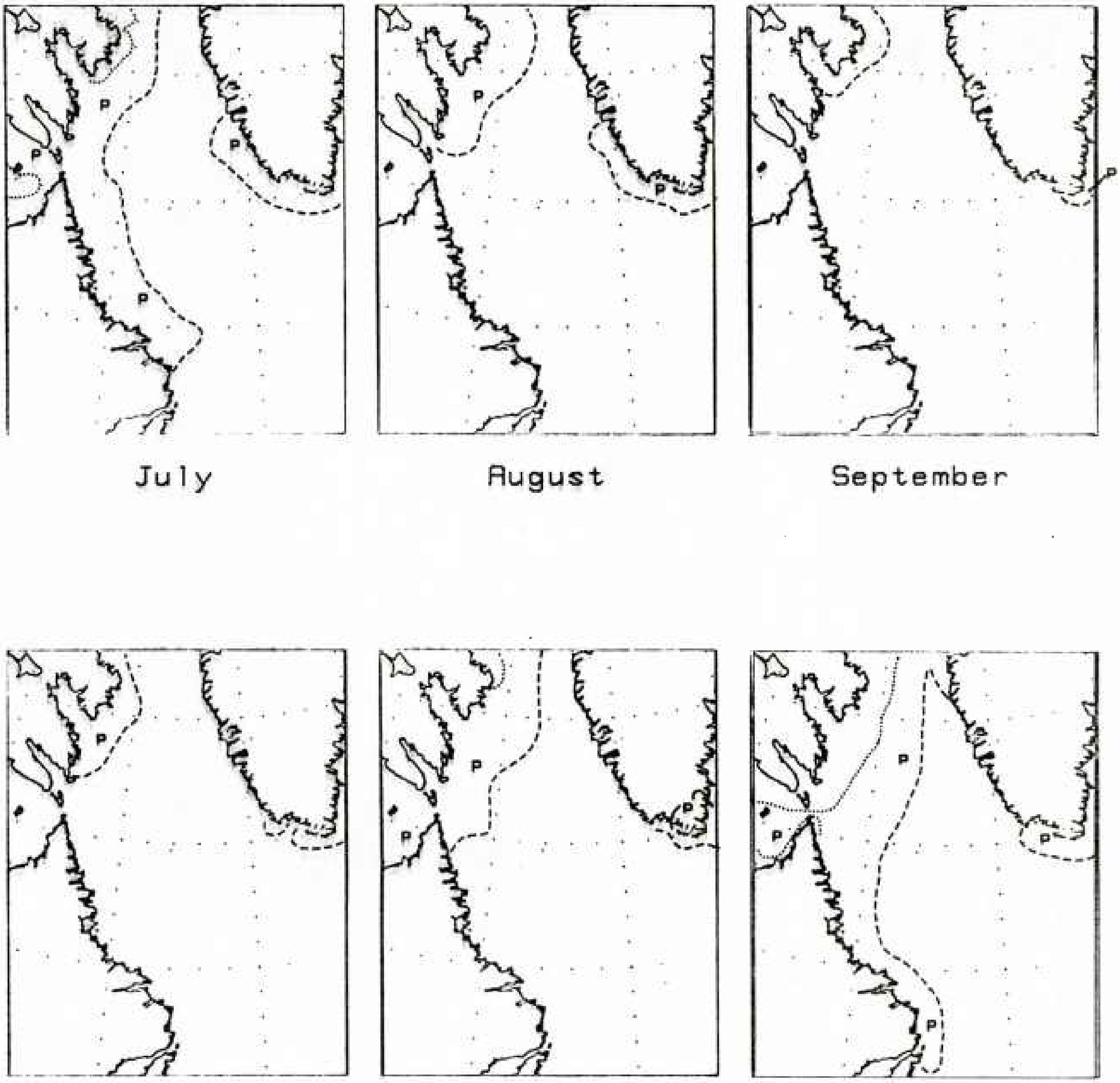


Figure I.1. Labrador Sea monthly average ice cover.



July August September

October November December

Figure I.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix J: Baffin Bay/Davis Strait

Boundaries of Baffin Bay/Davis Strait are
north—Smith Sound;
south—Labrador Sea;
east—west coast of Greenland;
west—east coast of Ellesmere and Baffin Island.

Oceanography

The maximum depth found in the Baffin Basin is 2012 m. In this region the warmer waters from the Atlantic meet the colder Arctic waters. Surface waters show a wide range of variation due to local effects of summer heating, winter cooling, and changing ice concentrations. In general, surface water has variable temperatures from – 1.0°C to 5.0°C and salinity of 30.0 to 33.5 ppt. Below the surface water, a cold water mass occupies the depth range of 50 to 200 m, with temperatures to – 1.6°C and salinity near 33.8 ppt. The higher salinity at this depth compared to water at the same level in the Arctic Ocean indicates that this water does not enter Baffin Bay from the north but is the result of local weather conditions and the general circulation pattern. Below 200 m depth, a warm intermediate layer is defined by temperatures greater than – 0.5°C and salinity 34.2–34.5 ppt. At depths greater than 1000 m the temperature decreases to less than – 0.5°C, and salinity is practically constant at 34.45 ppt.

Circulation

The general circulation in Baffin Bay is counterclockwise. The West Greenland Current transports warm Atlantic water along the eastern boundary of the region. After this current has reached the northern extremes of Baffin Bay most of the heat is dissipated, but it is still warmer and more saline than the waters flowing southward from the Arctic Ocean. The confluence of these two waters forms the Canadian Current, which flows southward along Baffin Island Coast. It is a cold current that carries sea ice and icebergs. South of Davis Strait the Canadian current is joined by the warm waters of the West Greenland Current to form the Labrador Current. The general circulation pattern is shown in Figure 2.1 of the main text.

Sea ice

The Baffin Bay/Davis Strait region has considerable contrast between ice conditions on the east and west sides. As a result of the warm West Greenland Current the eastern region of Davis Strait may remain ice free all year as far north as 70°N. During this time fast ice will usually form in the fjords. The cold Arctic water brought southward by the Canadian Current is responsible for the western region being ice covered. Apart from the icebergs, the sea ice in Baffin Bay is mostly first-year ice, except for the small portion that may remain from one year to the next and the older ice entering from Nares Strait.

Ice formation begins in the north in late September and advances southward to Davis Strait by mid-October. Maximum sea ice thickness occurs in late April and is about 1.5 m in northern Baffin Bay and about 1.3 m in Davis Strait. Ice conditions can change rapidly due to varying winds and has a general net drift to the south about 8 km per day along the west side of the bay. The prevailing northerly winds maintain an open water patch in Smith Sound (north Baffin Bay) known as "North Water." Ice melting begins in June. The east coast of Baffin Island may have ice remaining throughout the summer, but usually all ice is gone by September.

Icebergs are prevalent in Baffin Bay, with greatest concentration near the source areas of Disko Bay and Melville Bay. They drift north in the West Greenland Current, cross the Bay, and drift south with the Canadian Current toward the Grand Banks. Monthly average ice cover for Baffin Bay/Davis strait is shown in Figure K.1.

Detailed sea ice information for Baffin Bay can be found in *Sea Ice Atlas of Northern Baffin Bay*, 1982. Hajime Ito, Dept. of Geology, Swiss Federal Institute of Technology, Zurich CH-8092 Zurich, Switzerland.

Climatology

The climate of Baffin Bay is polar maritime. Temperatures are warmer in all months in the vicinity of Davis Strait and proceed to get colder toward the north and along the Canadian side of the Bay. Extremely high winds occur frequently along the Greenland coast where the icecap approaches the coast. These often exceed 35 m/sec and can rise quickly. Precipitation is greatest in the area near Davis Strait on the Canadian side and is generally light elsewhere in the region. Visibility of less than 2 km occurs about 80 days/year, with frequent fog and low overcast in the summer.

Temperatures

Winter	–53°C to –12°C
Summer	–12°C to 10°C

December to March are coldest and May to September mildest.

Range of mean daily temperatures is –53°C to 10°C.

Lowest recorded temperature is –60°C.

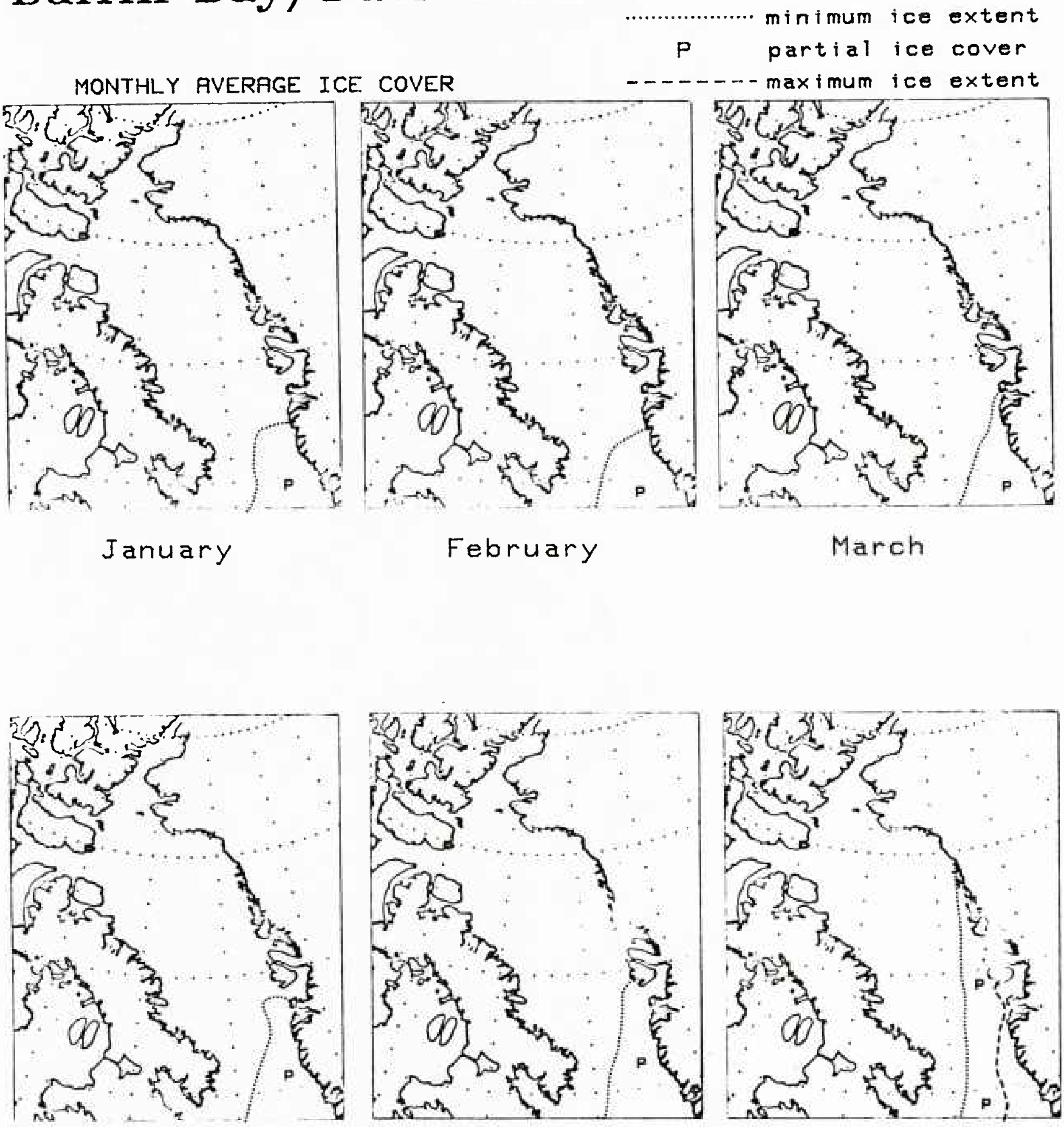
Winds

Winter	1 to 3 m/sec W to NW
Summer	1 to 8 m/sec E

Sea state

Seas are usually less than 1 m in winter and greater than 1.5 m from 10 to 20% of the time in summer.

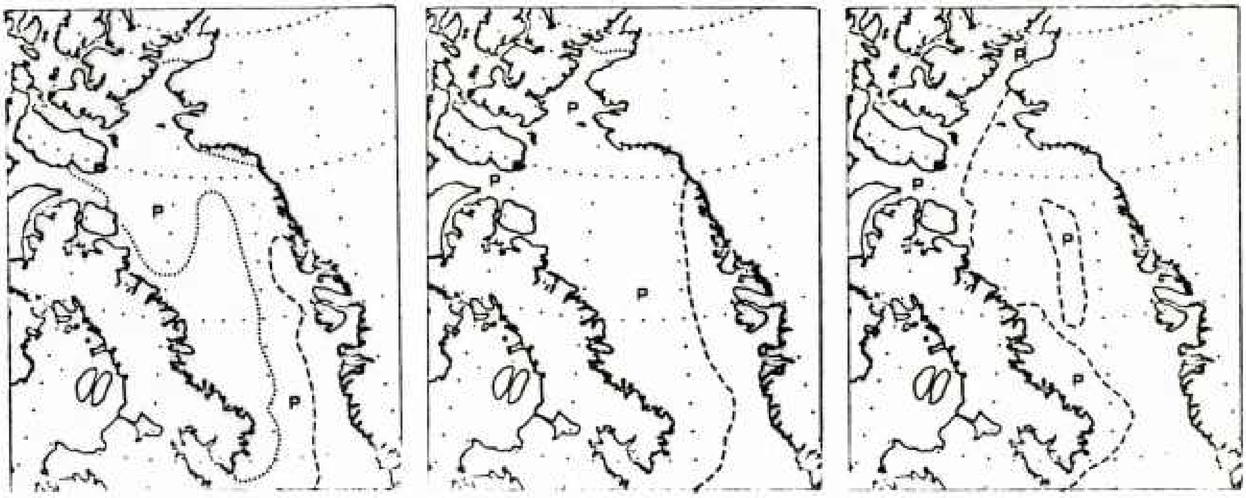
Baffin Bay/Davis Strait



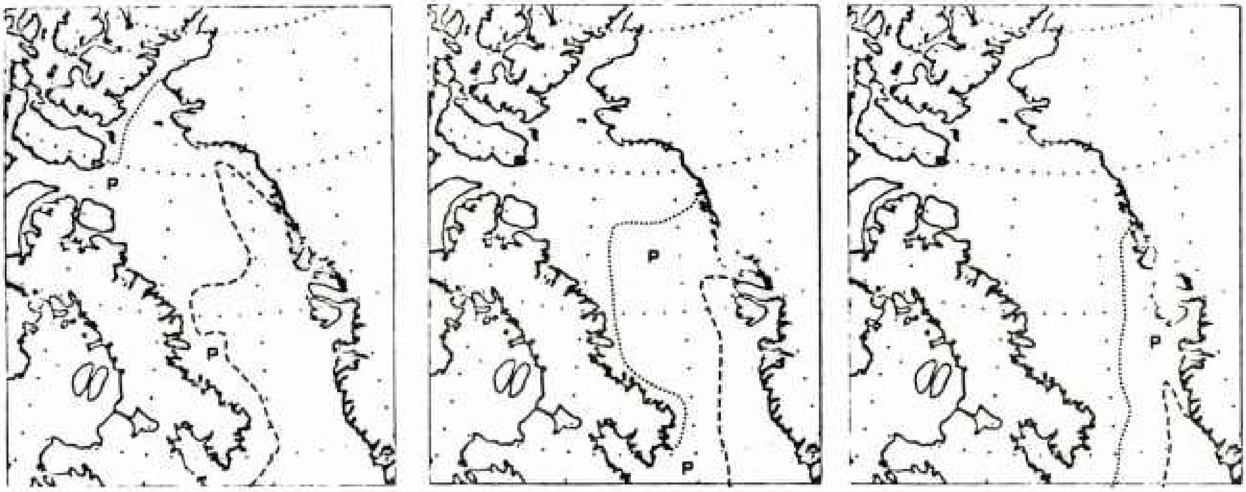
January February March

April May June

Figure J.1. Baffin Bay/Davis Strait monthly average ice cover.



July August September



October November December

Figure J.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix K: Bering Sea

Boundaries of the Bering Sea are
north—Bering Strait;
south—Alaska Peninsula, Aleutian Island Arc;
east—Alaska;
west—Siberia.

Oceanography

The Bering Sea has an area of 2.3 x 10^6 km^2, a volume of 3.7 x 10^6 km^3, and an average depth of 1636 m.

The main factors affecting the distribution and variation of the physical properties of these waters are currents and the seasonal changes in solar heating of the waters. The Oyashio Current brings cold, low-salinity water from the northern Bering Sea southwestward along the coast of the Kamchatka Peninsula. During winter, the surface waters are chilled by radiant heat loss and high evaporation. As the water is cooled, it becomes more dense and sinks into the less dense water below. Warmer water moves up to replace the cooled surface water, and it in turn cools and sinks. This convective mixing process continues until all the water in the column to depths of approximately 100 m becomes isothermal, isohaline, and isopycnic, and the surface waters become cool enough for ice to form. This winter cooling of the surface waters forms a deep layer of minimum temperatures (less than $-1.1°C$).

Surface salinities are at a maximum in winter and early spring with values higher than 33.00 ppt. Strong positive salinity gradients are common in the water column. These vary in strength and depth according to the season and location. In April (maximum ice conditions) these gradients start within the upper 200 m of the water column and are strongest in the upper 500 m. Below 500 m the change is more gradual, with maximum values of 34.60–34.75 ppt at approximately 3000 m.

Low surface temperatures in the winter and early spring cause positive sound velocity gradients. In spring, the formation of shallow thermoclines is reflected in the sound velocity structure by a weak near-surface sound channel.

Detailed oceanographic information can be found in *Environmental Guide NP-5, Bering Sea (U)*, U.S. Naval Oceanographic Office, NSTL, Mississippi, SP 3160-NP5, 1983. SECRET

Circulation

Current flow into the Bering Sea converges with water moving northward in the Western Subarctic Gyre and results in the formation of a cyclonic eddy over the western Aleutian basin and an anticyclonic eddy in the vicinity of the North Rat Island Ridge. The main flow continues northward around the ridge and turns eastward, and establishes the general cyclonic circulation over the deep basin. In the eastern part of the sea, cyclonic and anticyclonic eddies are created as the current turns northward adjacent to the continental shelf; in the northern part the current diverges and sends one branch northward toward Bering Strait and the other southwestward along the shores of Kamchatka, where it eventually becomes the East Kamchatka Current and discharges back into the North Pacific Ocean. Currents over the continental shelf off the Alaskan coast are chiefly tidal, except adjacent to the coastline where runoff from the Alaskan coast flows northward and is discharged through Bering Strait. Speeds up to 300 cm/sec have been observed near the eastern side of the strait. The flow is approximately 3–4 times greater during August and September than in February and March when ice is present. The principal characteristics of this current, which supplies about 20% of the inflow into the Arctic basin, can generally be explained in terms of the prevailing winds above the Arctic basin. In the extreme western part of the strait, a southward-flowing countercurrent, or "polar" current, is occasionally observed. Currents at depth are not well known.

Sea ice

The seasonal ice coverage reaches a maximum during the second week of April in the Bering Sea. The ice edge is frequently irregular because bands of heavier ice floes extend outward from the main ice pack. No glacier ice is found in this area, and first-year ice types are dominant during the spring season. The maximum average thickness of sea ice varies from 0.3 to 1.3 m. Ice hummocks occur throughout the sea and can attain heights of 3–6 m. Ice pressure ridges may make surface navigation difficult and many regions become impassable. Most of the sea ice is confined close to shore, but may drift to the open ocean.

Monthly average ice cover for the Bering Sea is shown in Figure K.1.

Climatology

The climate of the Bering Sea varies dramatically from south to north. The area adjacent to the Aleutian Islands is prone to frequent storms, dense fog, and accompanying high seas, while the area north of St. Lawrence Island is relatively storm free and calm due to the presence of a partial sea ice cover for a large part of the year. Short periods of very good weather occur, but the sky is usually overcast and fog is frequent. Visibility is less than 2 km for about 73 days/year.

Temperatures

Winter	–23°C to 3°C (February is coldest)
Summer	4°C to 14°C (July is warmest)

Range of mean daily temperatures is –23°C to 14°C. Temperatures may be less than –23°C 5 days/year.

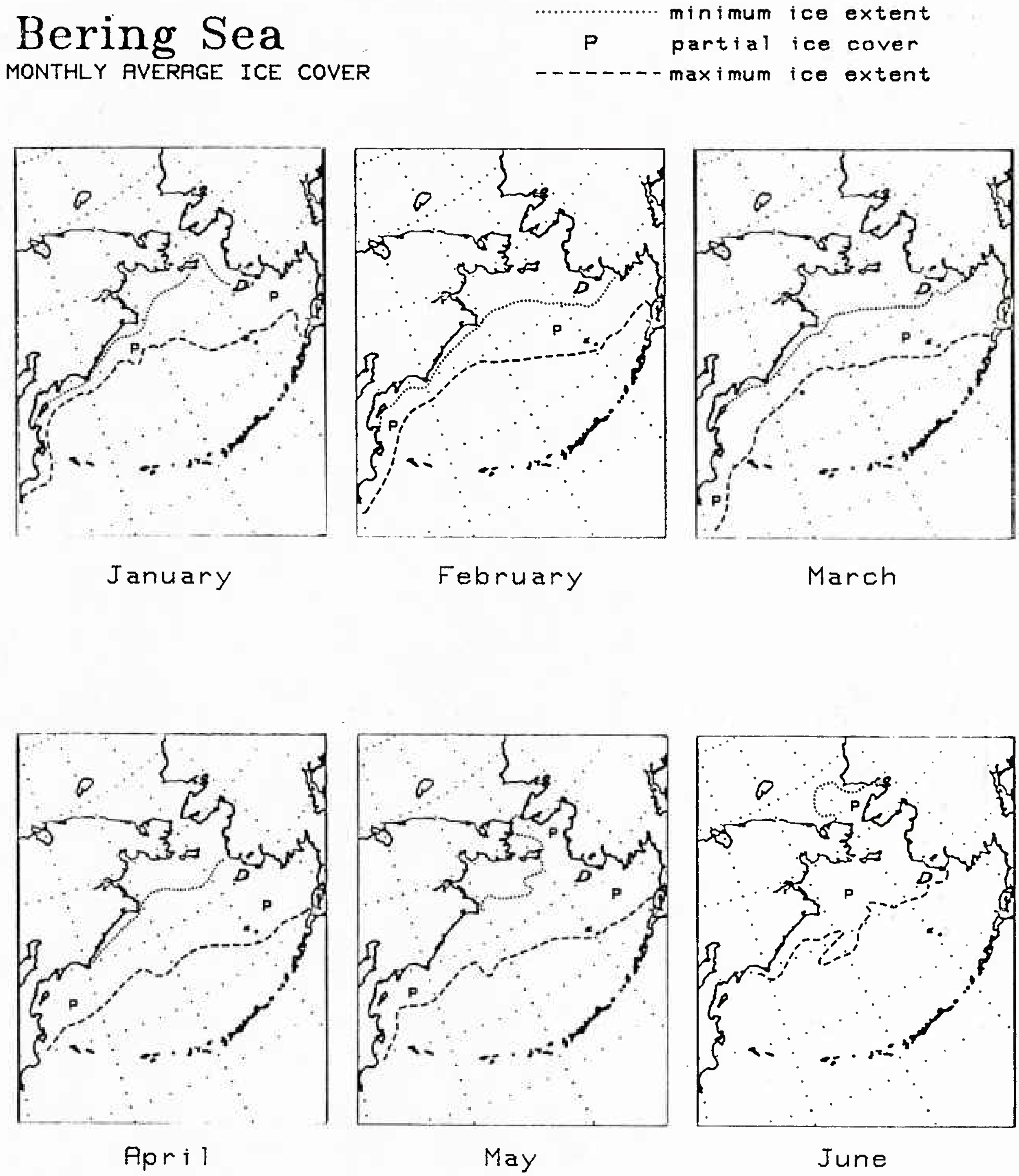
Winds

Winter	1.5 to 7 m/sec N to NE
Summer	1.5 to 10 m/sec Southerlies

Strongest winds occur in July.

Sea state

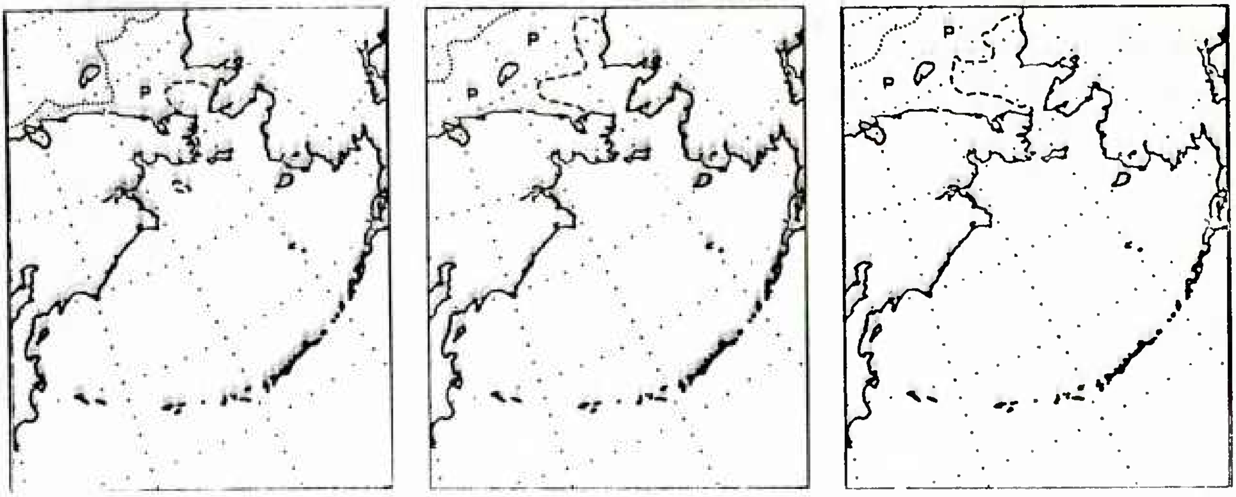
The southern section of the Bering Sea experiences seas in excess of 1.5 m from 60 to 80% of the time in summer and 70 to 80% of the time in winter. The northern part has seas greater than 1.5 m 40% of the time in summer and is normally ice covered in winter.



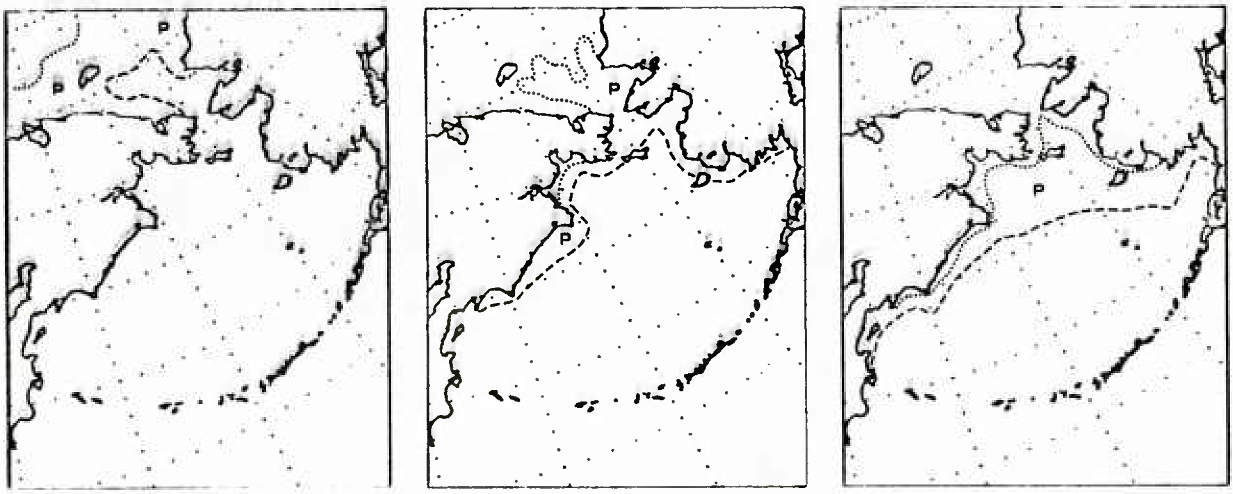
January February March

April May June

Figure K.1. Bering Sea monthly average ice cover.



July August September



October November December

Figure K.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix L: Norwegian Sea

Boundaries of the Norwegian Sea are

north and east—Norway Coast from North Cape (25°45′E) to Bear Island and the south point of West Spitsbergen (Svalbard);

west—south point of West Spitsbergen to Jan Mayen Island and thence to Gerpir in Iceland (65°05′N, 13°30′W);

south—Gerpir, Iceland, to the Faeroe Islands (Fugloe, 6°21′S, 6°15′W), and thence to the intersection of 61°00′N at 0°53′W (just north of the Shetlands), following this parallel to the coast of Norway just south of Sogne-Fjord.

Oceanography

Water masses of the Norwegian Sea consist of North Atlantic Water and Norwegian Deep Water. The latter is formed in winter in the western part of the sea near Jan Mayen Island. It has salinity values of 34.90–34.94 ppt and is formed by mixing Atlantic and Arctic water. Atlantic water entering the Norwegian Sea is 35.4 ppt and decreases to the north by mixing with coastal water from the central parts of the sea. The salinity below 600 m is about 34.90 ppt and is almost uniform.

Water temperature below 100 m is not influenced by surface heating processes and, in general, is above 4°C. In the southern part it is between 8 and 9°C and decreases to about 6°C off northern Norway. Below 600 m, the temperature is about −1°C and is almost uniform. Below a depth of less than 1000 m the deep water of the Norwegian Sea is cut off from the Atlantic Ocean, except for occasional southward outflows across the Faeroe-Iceland Ridge.

The warm, saline Atlantic water entering the sea via the North Atlantic Current is responsible for the year-round ice-free condition (Fig. L.1).

Detailed sound speed profiles can be found in *Sound Speed Profiles for the Norwegian Sea*, June 1979. Naval Undersea Systems Center, New London, Connecticut, NUSC Technical Document 6035 (second printing April 1981).

Circulation

The Norwegian Coastal Current flows northward along the west coast of Norway and is paralleled on the outside by the Norwegian Atlantic Current. Both are branches of the North Atlantic current and surface velocities are about 30 cm/sec. The total volume of Atlantic water entering the Norwegian Sea is 3–6 million m^3/sec with great annual variations. The Norwegian Atlantic Current carries warm Atlantic water and splits into two branches in the vicinity of 70°N. One branch continues as the West Spitsbergen current; the other branch turns eastward and merges with the Norwegian Coastal Current to form the relatively warm North Cape Current, which then carries on into the Barents Sea. In the central portion of the Norwegian Sea, there is a distinctive cyclonic gyral (the Norwegian Gyral) between the Norwegian Atlantic Current and a branch of the Greenland Current, which flows southeast north of Iceland with the center lying around 68°N, 13°W. The volume transport across a section between Iceland and the Faeroe Islands is southward and varies between 4.5 and 6.2 million m^3/sec.

General circulation is shown in Figure 2.1 of the main text.

For specific surface current data for the Norwegian Sea see *Surface Currents Norwegian and Barents Seas*, U.S. Naval Oceanographic Office, NSTL, Mississippi, Special Publication 1400-NA2, January 1978 (reprinted 1980).

Climatology

The air mass over the Norwegian Sea is polar maritime. In summer the Arctic frontal zone runs from Iceland to the northern part of Norway, and storms frequently pass on both sides of the zone. Precipitation is quite frequent all year compared with the land areas and the Greenland Sea at the same latitude. The predominant surface winds are northerly to northeasterly in the northern part, but south of the Arctic frontal zone it is south to southwest. Visibility is less than 2 km for about 160 days/year.

Temperatures

Winter	−1°C to 4°C
Summer	−1°C to 10°C

Range of mean daily temperatures is −1°C to 10°C.

Lowest recorded temperature is −12°C.

Winds

Winter	1 to 4 m/sec
Summer	1 to 4 m/sec

Wind direction is quite variable throughout the year and is associated with weather systems passing through the area.

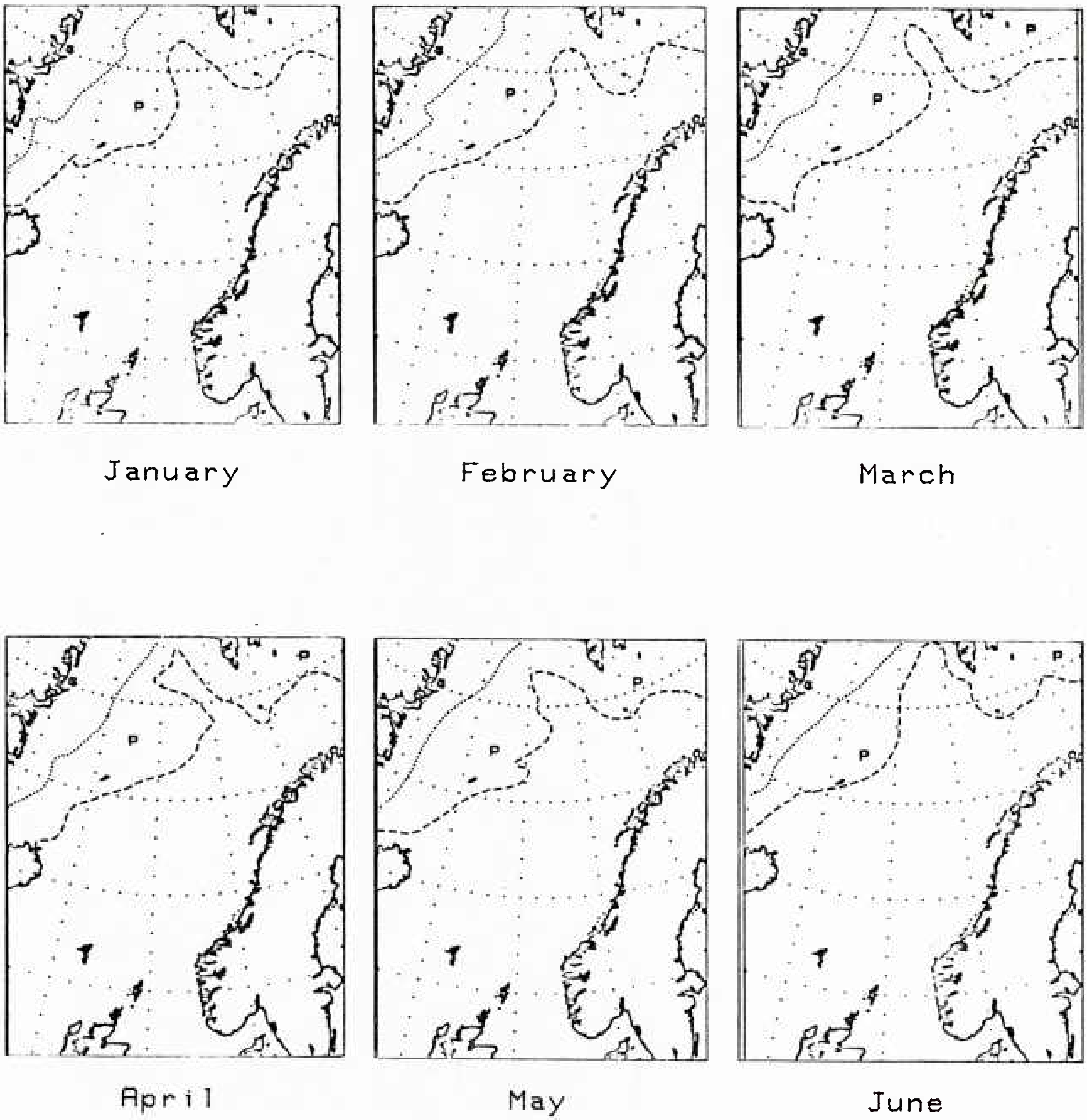
Sea state

Seas in excess of 1.5 m occur from 10 to 40% of the time in summer and from 30 to 60% in winter.

Norwegian Sea

MONTHLY AVERAGE ICE COVER

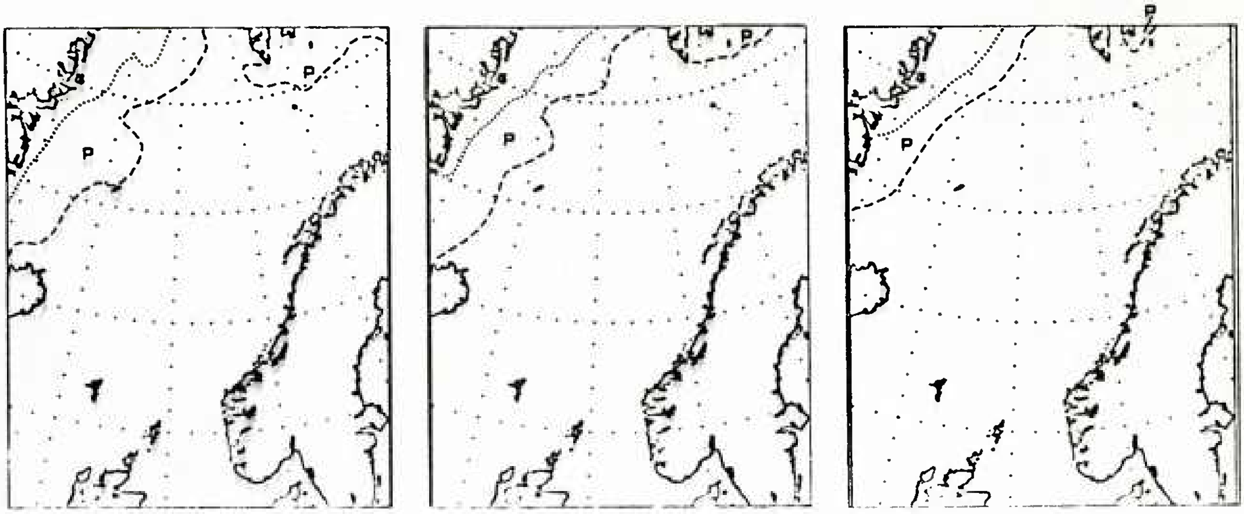
········ minimum ice extent
P partial ice cover
-------- maximum ice extent



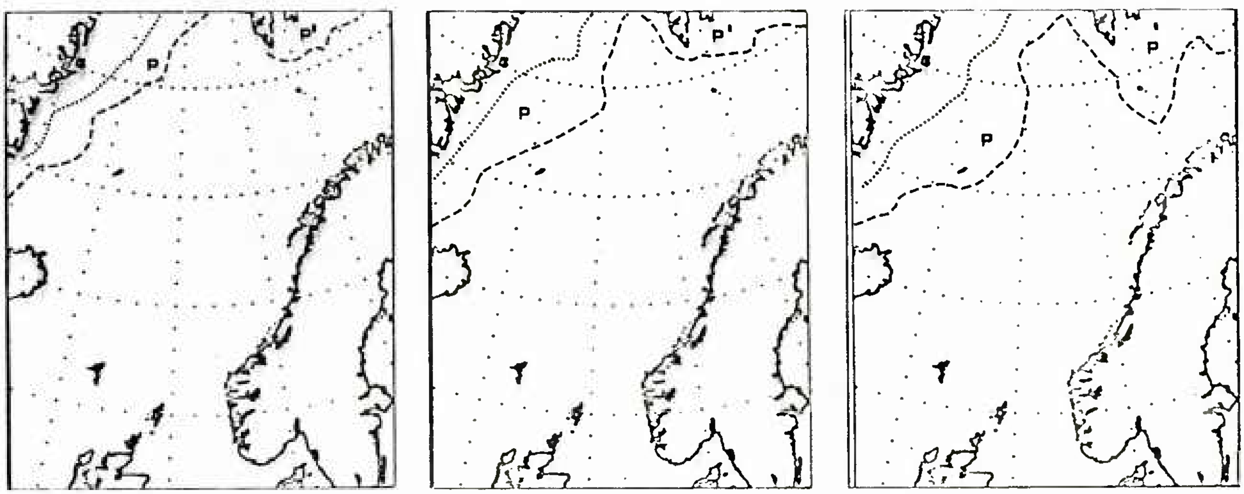
January February March

April May June

Figure L.1. Norwegian Sea monthly average ice cover.



July August September



October November December

Figure L.1. Cont'd.

Source: Compiled at NORDA from information supplied by Naval Polar Oceanography Center, Suitland, Maryland.

Appendix M: Central Arctic

Oceanography

The Central Arctic refers to the area of the Arctic Ocean around the geographic north pole excluding the marginal seas. It is comprised of the three water masses discussed in section 2 in the main text. In brief, these masses are

- Arctic water; surface layer, cold (at or near freezing point), relatively dilute (28–32 ppt).
- Atlantic water; approximately 150–900 m, 0°–3°C, quite uniform salinity (34.9–35.1 ppt).
- Bottom water; approximately 900 m to bottom, nearly uniform temperatures from −0.70°C to −0.80°C, nearly uniform salinity (34.9 to 34.99 ppt).

A fourth water mass, known as Pacific Water, is sometimes distinguished on the Alaskan-Canadian side of the ocean. It underlies the surface layer and is slightly warmer, −0.7°C at about 70 m. Water temperatures are always near the freezing point and salinity is the controlling factor in water density. Warm, saline water enters the Arctic Ocean northwest of Svalbard where its greater density causes it to sink beneath the surface. It then spreads across the Arctic Ocean at a level appropriate to its density. This water loses its heat and salinity as it mixes upward with the surface waters, which are cooled by loss of heat to the atmosphere and freshened by precipitation and river run-off. The surface water then flows southward out of the Arctic Ocean as the East Greenland Current. Central Arctic sea ice, circulation, and climatology are discussed in sections 1, 2, and 3 of this report.

Appendix N: Bibliography

The following bibliography is primarily to aid the reader in finding specific and more inclusive information regarding each Arctic marginal sea.

Barents Sea

Batten, E. S. (1976). *Sea-Ice Conditions in the Norwegian, Barents, and White Seas.* Defense Advanced Research Projects Agency, Rand Corp., Santa Monica, California, Report No. R-1921-ARPA.

Boris, L. I. (1976). Statistical Prediction of Large Anomalies of Hydrometeorological Characteristics. Leningrad, Glavnaya Geofizicheskaya Observatoriya, *Trudy*, n. 380, pp. 43–55.

Eldholm, Olva and Manik Talwani (1975). *Sediment Distribution and Structural Framework of the Barents Sea.* Fleet Weather Facility Suitland, Maryland, June 1976, *Eastern Arctic Sea Ice Analyses* 1972–1975. Lamont-Doherty Geological Observatory, Palisades, New York, Report No. LDGO-2484.

Eldholm, Olva and John Ewing (1971). Marine Geophysical Survey in the Southwestern Barents Sea. *J. Geophys. Res.*, v. 76, n. 17, June 10.

Ershtadt, T. A. (1965). On the Adaptability of the Dynamic Method of Calculating Elements of Sea Currents in the Barents Sea. Moscow, Gosudarstvennyi Okeanograficheskii Institut, *Trudy*, n. 86.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography*. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Foster, Leslie A., Ola M. Johannessen, and Cinzia Isoppo (1974). *Oceanographic Summary of the Barents Sea South of Bear Island in the Summer.* Saclant ASW Research Centre, La Spezia, Italy, Report No. SACLANT-CEN-SM-52.

Garcia, Andrew W. (1969). *Oceanographic Observations in the Kara and Eastern Barents Seas.* Coast Guard, Wash. Ocean. Unit, Monitor: USCG-373-25.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, New York: Springer-Verlag, 397 p.

Johannessen, Ola M. and L. A. Foster (1978). Note on the Topographically Controlled Oceanic Polar Front in the Barents Sea. *J. Geophys. Res.*, v. 83, n. C9, pp. 4567–4571.

Kaminski, H. (1976). Remote Sensing of Variations of Sea-Ice-Surfaces in the Barents Sea from 1966–1975 by Means of Satellite Data, among others NOAA-VHRR. Presented at the *10th International Polar Meeting*, Zurich, Switzerland.

King, R. E. (1977). Norwegian and Barents Seas: Oil for the 21st Century? *World Oil*, v. 185, n. 7, pp. 69, 72, 74, 76.

Klenova, M. V. (1961). *Geology of the Barents Sea.* U. S. Naval Oceanographic Office, NSTL, Mississippi, Report No. NOO-Trans-130.

Lastochkin, A. N. (1978). Submarine Valleys on the Northern Continental Shelf of Eurasia. *Polar Geography*, v. 2, n. 4, p. 240–250.

Lebedev, A. A. and N. S. Uralov (1973). Short-Term Changes in the Ice Edge in the Barents Sea. Leningrad Arkticheskiy i Antarkticheskiy Nauchno-Issledovatel'skiy Inst., *Trudy*, v. 307, p. 63–72.

Loeng, H. (1980). Physical Oceanographic Investigations in Central Parts of the Barents Sea, July 1979. *Fisken Og Havet*, pp. 29–60.

Loeng, H. (1979). A Review of the Sea Ice Conditions of the Barents Sea and the Area West of Spitsbergen. *Fisken Og Havet*, n. 2, pp. 29–75.

Loeng, H. and T. E. Vinje (1980). *On the Sea Ice Conditions in the Greenland and Barents Seas.* Inst. of Marine Research, P. O. Box 2906, N-5011 Bergen, Norway, pp. 163–176, 80-07046.

Lyubarskiy, A. N. (1976). Ice Fluctuations in the Barents Sea and the Possible Physical Causes. Leningrad, Glavnaya Geofizicheskaya Observatoria, *Trudy*, n. 380, pp. 81–88.

Moskal', T. N. (1973). Forecasting Ice Conditions in Northeast Regions of the Barents Sea in Winter–Spring Months. Leningrad, Arkticheskiy i Antarkticheskiy Nauchno-Issledova-tel'skiy Inst., *Trudy*, v. 307, pp. 76–78.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

Norina, A. M. (1968). *Hydrological Characteristics of the Northern Barents Sea*. U. S. Naval Oceanographic

Office, NSTL, Mississippi, Report No. NOO-Trans-373.

Perry, R. K., H. S. Fleming, R. H. Feden, and N. Z. Cherkis (1978). Bathymetry of the Norwegian-Greenland and Western Barents Sea. *EOS (Transactions of the Am. Geophys. Union)*, v. 59, n. 4, 377 pp.

Pitcher, M. G. (1971). *Arctic Geology.* Published by the American Association of Petroleum Geologists, Tulsa, Oklahoma, 1973.

Rey, L. (ed.) (1982). *The Arctic Ocean.* John Wiley and Sons, New York.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* The Arctic Institute of North America, Washington, D.C.

U.S. Naval Oceanographic Office (1978). *Surface Currents Norwegian and Barents Seas.* NSTL, Mississippi, reprinted 1980, NOOSP14000-NA2.

Beaufort Sea

Campbell, W. J. (1974). Dynamics and Morphology of Beaufort Sea Ice Determined from Satellites, Aircraft, and Drifting Stations. University of Washington, *AIDJEX Bull.*, n. 25, pp. 1–27.

Coachman, L. K. and J. L. Newton (1972). *Water and Ice Motion in the Beaufort Sea, Spring 1970.* Office of Naval Research, Washington, D.C., Technical Report No. TR-4, *AIDJEX Bull.*, No. 12.

Dehn, W. S. (1974). Ice Forecasting in the Beaufort Sea. *Arctic Inst. of North Am. Conf.*, 07–09 January, n. 74-0216.

Dugas, J. A. and D. C. Burrell (1976). *Dynamic Sedimentological Processes Along the Beaufort Sea Coast of Alaska.* Alaska University, Inst. Mar. Sci., Occas. Publ. 4, pp. 189–203.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Gatto, Lawrence W. (1980). *Coastal Environment, Bathymetry, and Physical Oceanography Along the Beaufort, Chukchi, and Bering Seas.* CRREL Special Report No. CRREL-SR-80-5.

Herlinveaux, R. H., Boom De Lange, and G. R. Wilton (1976). *Water Movements in the Beaufort Sea: Summer 1974, Spring and Summer 1975.* Canada, Mar. Sci. Directorate, Victoria, B.C., Pacific Marine Sci. Rep. 76-27.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Kusunoki, Kou (1962). *Hydrography of the Arctic Ocean with Special Reference to the Beaufort Sea.* Hokkaido Univ., Inst. Low Temperature Sci. Contr. Ser. A, n. 17, p. 75.

Milne, A. R. (1976). *Canadian Environmental Studies of the Southern Beaufort Sea.* Alaska, Univ., Inst. Mar. Sci., Occas. Publ. 4, pp. 87–94.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

NOAA, Bureau of Land Management (1975–1978). *Environmental Assessment Series of the Alaskan Continental Shelf.*

O'Rourke, Cameron J. (1974). *Inventory of Physical Oceanography of the Eastern Beaufort Sea.* Arctic. Inst. of North Am., Washington, D.C., pp. 65–84.

Reimnitz, E., L. Toimil, and P. Barnes (1978). *Arctic Continental Shelf Morphology Related to Sea-Ice Zonation, Beaufort Sea, Alaska.* Mar. Geol. (Amsterdam), v. 28, n. 3–4, pp. 179–210.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Sater, John E. (1974). Beaufort Sea Symposium Report. *Coastal Res. Notes*, v. 4, n. 2, pp. 1–3.

Sellmann, Paul V. (1980). *Regional Distribution and Characteristics of Bottom Sediments in Arctic Coastal Waters of Alaska. Review of Current Literature.* CRREL Rept. No. CRREL-SP-80-15.

Sobczak, L. W. (1977). Ice Movements in the Beaufort Sea 1973–1975: Determination by ERTS Imagery. *J. Geophys. Res.*, v. 82, n. 9.

Tucker, W. B., III, W. F. Weeks, and M. D. Frank (1979). *Sea Ice Ridging Over the Alaskan Continental Shelf.* CRREL Rept. No. CRREL-79-8.

Weller, Gunter (1974). Outer Continental Shelf Environmental Assessment Program in the Beaufort Sea. *Arctic Bull.*, v. 2, n. 9, pp. 125–142.

Wilson, H. P. (1974). *Winds and Currents in the Beaufort Sea.* Arctic Inst. of North Am., 07–09 January, n. 74-0216.

Chukchi Sea

Aagaard, K. (1964). *Notes on the Physical Oceanography of the Chukchi Sea.* U. S. Coast Guard Oceanographic Rept. #1, pp. 13–16, Bibliog.

Black, D. I. (1968). *Gravity and Magnetic Observations from Ice Island Arlis II Off the Chukchi Shelf.* Arctic Inst. of North Am., Office of Naval Research, pp. 459–470.

Bourke, R. H. and R. G. Paquette (1976). Atlantic Water on the Chukchi Shelf. *Geophys. Res. Lett.*, v. 3, n. 10, pp. 629–632.

Brower, William A., Jr., Henry F. Diaz, Anton S. Prechitel, Harold W. Searby, and James L. Wise (1977). *Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska, Volume III, Chukchi-Beaufort Sea.* Arctic EIDC Final Rept. No. AEIDC-B-77-VOL-3.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Fleet Weather Facility, Rept. for January 1972–December 1975 (1976). *Western Arctic Sea Ice Analyses 1972–1975 Rept.*

Garrison, G. R., M. L. Welch, and J. T. Shaw (1979). *Oceanographic Measurements in the Chukchi Sea, April–August 1977.* Applied Physics Lab., University of Washington, Technical Rept. No. APL-UW-7824.

Garrison, G. R. (1976). *Chukchi Sea Oceanography: 1975 Measurements and a Review of Coastal Current Properties.* Applied Physics Lab., University of Washington, APL Rept. No. APL-UW-7614, Data presentation and analysis report.

Garrison, G. R. and P. Becker (1976). Barrow Submarine Canyon: A Drain for the Chukchi Sea. *J. Geophys. Res.*, v. 81, n. 24, pp. 4445–4453.

Garrison, G. R., J. T. Shaw, and M. L. Welch (1982). *Arctic Oceanographic Measurements: 1978–1980.* Applied Physics Laboratory, University of Washington, APL Rept. No. APL-UW-8112.

Gatto, Lawrence W. (1980). *Coastal Environment, Bathymetry, and Physical Oceanography along the Beaufort, Chukchi, and Bering Seas.* CRREL Rept. No. CRREL-SR-80-5.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Hufford, G. L. (1977). Northeast Chukchi Sea Coastal Currents. *Geophys. Res. Lett.*, v. 4, n. 10.

Hunkins, K. L. (1965). Tide and Storm Surge Observations in the Chukchi Sea. *Limnology and Oceanography*, v. 10, n. 1, pp. 29–39.

Naval Arctic Manual, (1970). ATP-17-(A) COMTAC Publication.

NIS-105, Part VIII, Section 2 (1969). *Bering and Chukchi Sea Oceanography (U).* SECRET

Paquette, R. G. and R. H. Bourke (1978). Temperature Fronts in the Marginal Sea Ice Zone of the Chukchi Sea. *EOS, Transactions of the Am. Geophysical Union*, v. 59, n. 12, pp. 1091–1092.

Pence, E. A. (1973). *Studies in the Marginal Ice Zone of the Chukchi Sea.* Acoustic and Oceanographic Data for 1972, Gov. Rep. Announcements, v. 73, n. 22, p. 95.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Tucker, W. B., III, W. F. Weeks, and M. D. Frank (1979). *Sea Ice Ridging Over the Alaskan Continental Shelf.* CRREL Rept. No. CRREL-79-8.

Kara Sea

Dvorkin, E. N., Yu. V. Zakharov, and N. V. Mustafin (1979). Seasonal and Long-Term Variability of the Level of the Kara Sea. Leningrad, Arkticheskiy i Antartkicheskiy Nauchno-Issledovatel'skiy Inst., *Trudy*, v. 361, pp. 63–71.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Gedeonov, A. D. and V. S. Nazarov (1969). *Eighty-Year Cycle of Mean Monthly Air Temperature in the Northern Hemisphere and Historical Variation of Ice-Conditions in the Kara Sea.* Defense Scientific Info. Service, Ottawa, Rept. No. T-525-R.

Hanzlick, D. and K. J. Aagaard (1980). Freshwater and Atlantic Water in the Kara Sea. *J. Geophys. Res.*, v. 85, n. C9.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Johnson, G. Leonard and Donald B. Milligan (1967). Some Geomorphological Observations in the Kara Sea. *Deep-Sea Res.*, v. 14, n. 1, pp. 19–28.

Kirillov, A. A. and V. A. Slichkin (1973). Forecasting Ice Distribution in the Southwestern Kara Sea. Leningrad, Arkticheskiy i Antartkicheskiy Nauchno-Issledovatel'skiy Inst., *Trudy*, v. 307, pp. 79–82.

Kulikov, N. N. (1967). *Sedimentation in the Kara Sea.* U. S. Naval Oceanographic Office, NSTL, Mississippi, NOO-Trans-317, 18 pp.

Lastockkin, A. N. (1977). Bottom Topography of the Kara Sea. *Geomorfologiya* (Moscow) 2, pp. 84–91,

Milligan, Donald B. (1969). *Oceanographic Survey Results Kara Sea, Summer and Fall 1965.* U. S. Naval Oceanographic Office, NSTL, Mississippi, NOO-IR-217.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

Nazintsev, Yu. L. (1972). Snow Accumulation on Kara Sea Ice. *AIDJEX Bull.*, n. 17, pp. 77–83.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Stepanov, S. I. (1979). Relationship Between Heat Content and Heat and Water Transfer in the Kara Sea. Leningrad, Arkticheskiy i Antartkicheskiy Nauchno-Issledovatel'skiy Inst., *Trudy*, v. 361, pp. 55–58.

Troitsky, V. A. (1977). Dynamics of the South-Eastern Coasts of the Kara Sea. *Geomorfologiya* (Moscow), v. 1, pp. 82–86.

Greenland Sea

Aagaard, K. (1968). Circulation of the Greenland Sea. Military Oceanography, *Proceedings of U. S. Navy, Fifth Symposium*, v. I., Panama City, Florida, May 1–3.

Aagaard, Knut (1974). *Greenland Sea Studies.* Washington University, Department of Ocean., Final Technical Rept. No. Ref-M75-98.

Aagaard, Knut (1976). *Greenland Sea Studies, Part IV.* Washington University, Department of Ocean., Final Technical Rept. No. Ref-M76-66.

Aagaard, Knut (1970). Wind Driven Transports in the Greenland and Norwegian Seas. *Deep Sea Research and Oceanographic Abstracts*, v. 17, n. 2, pp. 281–291.

Aagaard, Knut (1972). *The Wind-Driven Circulation of the Greenland and Norwegian Seas and Its Variability.* See Citation n. 73-6B-01050, pp. 296–299.

Aagaard, Knut, Clark Darnall, and Paul Greisman (1973). *Year-Long Current Measurements in the Greenland-Spitsbergen Passage.* Office of Naval Research, Rept. No. TR-3, Contrib-711, 6 pp.

Aagaard, Knut (1972). *Greenland Sea Currents.* Washington University, Technical Rept., Project NR-307-342, 9 pp.

Bradley, D. L. and Colvin, G. M. (1972). Acoustic Measurements in the West Greenland Sea. Program of the *83rd Meeting of the Acoustical Soc. of Am.*, Buffalo, New York, 18–27 April.

Carmack, E. and K. Aagaard (1972). *The Formation of Bottom Water in the Greenland Sea.* Office of Naval Research, Rept. No. TR-315, 21 pp.

Carmack, Eddy and Knut Aagaard (1973). *On the Deep Water of the Greenland Sea.* Washington University, Department of Ocean., Rept. No., Contrib-713, 30 pp.

Coachman, L. K. (1968). The East Greenland Current North of Denmark Strait; Part II. *Arctic*, v. 21, n. 4, pp. 267–290.

Damuth, J. E. (1978). Echo Character of the Norwegian-Greenland Sea; Relationship to Quaternary Sedimentation. *Mar. Geol.*, v. 28, n. 1–2, pp. 1–36.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Fleet Weather Facility (1976). *Eastern Arctic Sea Ice Analyses 1972–1975.* Rept. for Jan 72–Dec 75.

Greisman, P. (1973). Year-Long Current Measurements in the Greenland-Spitsbergen Passage. *Deep-Sea Res. and Oceanographic Abstracts*, v. 20, n. 8, pp. 743–746.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Johnson, G. Leonard and Oscar B. Eckhoff (1966). Bathymetry of the North Greenland Sea. *Deep-Sea Research*, v. 13, n. 6, Pt. 1, pp. 1161–1173.

Kellogg, Thomas B. (1973). Climate of the Norwegian and Greenland Seas; Today and 17,000 Years Ago. *Geol. Soc. Am.* (Abs.), v. 5, n. 7, pp. 691.

Kirillov, A. A. and M. S. Khromtsova (1972). Many-Year Variation of the Ice Coverage of the Greenland Sea and Methods of Forecasting It. *AIDJEX Bull.*, n. 16, pp. 46–55.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

Newton, J. L. and L. E. Piper (1981). *Oceanographic Data From Northwest Greenland Sea: Arctic East 1979 Survey of the USCGS Westwing.* Sci. Appl., Inc., La Jolla, California, n. AD-A097 808/0.

Penin, V. V. (1972). *On the Question of Current Dynamics in the Norwegian and Greenland Seas.* Naval Research Laboratory, Rept. No. NRL-Trans-1257, 16 pp.

Perry, R. K., H. S. Fleming, N. Z. Cherkis, R. H. Feden, and J. V. Massingill (1978). Bathymetry of the Norwegian-Greenland and Western Barents Seas. *Geol. Soc. Am.*, Map Chart Ser. MC-21.

Sanderson, R. M. (1971). Ice-Edge Movements in the Greenland Sea. *Marine Observer*, London, v. 41, n. 234, pp. 173–183.

Sater, J. E. (ed.) (1966). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Skov, Niels Aage (1969). The Ice Cover of the Greenland Sea; An Evaluation of Oceanographic and Meteorological Causes for Year-to-Year Variations. *Diss. (Abs.)*, v. 28, n. 11, pp. 4683B–4684B.

Tripp, Richard B. and Kou Kusunoki (1967). *Physical, Chemical, and Current Data from Arlis II: Eastern Arctic Ocean, Greenland Sea, and Denmark Strait Areas, February 1964–May 1965, Vol. 1.* Washington University, Department of Ocean., Rept. No. TR-185-Vol-2; Ref-M67-29, 144 pp.

U.S. Naval Oceanographic Office (1978). *Surface Currents, Greenland Sea Including Denmark Strait.* Final Rept. No. NOO-SP-1400-NA-1.

Wadhams, P. (1981). The Ice Cover in the Greenland and Norwegian Seas. *Rev. Geophys. Space Phys.*, v. 19, n. 3, pp. 345–393.

White, S. M. (1978). Sediments of the Norwegian-Greenland Sea, DSDP Leg 38. *Initial Reports of the Deep Sea Drilling Project*, v. 38–41, Supplement, pp. 193–257.

Yanes, A. V. (1979). Thermal State of the Waters in the Northern Part of the Greenland Sea in February 1972 (According to Data of a Cross Section of the Barentsburg Ice Edge). Leningrad, Arkticheskiy i Antarkticheskiy Nauchno-Issledovatel'skiy Inst., *Trudy*, v. 361, pp. 37–42.

Zaripov. B. R. and D. G. Rzheplinskiy (1977). Long Term Average Seasonal Water Circulation of the Northeastern Atlantic and of the Norwegian, Greenland, and North Seas (Diagnostic Calculations). *Okeanologiya* (USSR), v. 17, n. 5.

Laptev Sea

Arikaynen, A. I. (1976). Methods of Long-Term Forecasts of Ice in the Laptev Sea. Leningrad, Arkticheskiy i Antartkicheskiy Nauchno-Issledovatel'skiy Inst., *Trudy*, v. 320, pp. 117–120.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography*. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Fedotov, V. I. (1976). Structure of One-Year Old Ice in the Laptev Sea in Spring. Leningrad, Arkticheskiy i Antartkicheskiy Nauchno-Issledovatel'skiy Inst., *Trudy*, v. 331, pp. 151–156.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology. Springer-Verlag, New York, 397 pp.

Lockerman, Robert C. (1968). *Some Summer Oceanographic Features of the Laptev and East Siberian Seas.* U.S. Naval Oceanographic Office, NSTL, Mississippi, Rept. No. NOO-TR-200, 57 pp.

Morozova, T. P. (1963). *Fluctuation of the Southern Boundary of Polar Ice in the Laptev Sea.* U.S. Naval Oceanographic Office, NSTL, Mississippi, Rept. No. NOO-Trans-126, 11 pp.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Zakharov, V. F. (1966). Some Features of the Estimated Ice Drift in the Laptev Sea. *Problemy Arktiki I Antarktiki*, Leningrad, n. 23, pp. 45–46.

Zakharov, V. F. (1967). The Role of Flow Leads Off the Edge of Fast Ice in the Hydrological and Ice Regime of the Laptev Sea. *Oceanology*, v. 6, n. 6, pp. 815–821.

Sea of Okhotsk

Akagawa, Masaomi (1970). On the Drift-Ice East of South Sakhalin in the Okhotsk Sea in June 1969 and Some Oceanographic Phenomena Related to the Sea Ice Situation. Hakodate, Japan, *Marine Observatory Bull.*, n. 15.

Aota, Masaaki (1974). On the Drift Ice of the Sea of Okhotsk. *Quat. Res. (Jap. Assoc. Quat. Res.)*, v. 12, n. 4, pp. 135–140.

Batalin, A. M. and N. G. Vasyukova (1964). *An Attempt to Calculate the Heat Budget of the Sea of Okhotsk.* U.S. Naval Oceanographic Office, NSTL, Mississippi, Rept. No. NOO-Trans-145, 22 pp.

Campbell, W. J. and R. O. Ramseier (1978). Structure and Motion of Bering and Okhotsk Sea Ice Covers by Microwave Satellite Imagery. Conf. Dates: 30 July to 4 August, n. 78-0041, *Bull., Am. Assoc. Pet. Geol.* (Tulsa), v. 62, n. 7, p. 1211.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Fleet Weather Facility (1976). *Western Arctic Sea Ice Analyses 1972–1975.* Rept. for Jan 72–Dec 75, 212 pp.

Gratz, A. J. and C. L. Parkinson (1981). *Oceanographic Influences on the Sea Ice Cover in the Sea of Okhotsk.* NASA, Goddard, Rept. No. NASA-TM-82085, 22 pp.

Hakodate, Japan, Marine Observatory (1977). Hakodate Marine Observatory: Sea Ice Observations in the Okhotsk Sea from December 1973 through April 1974. *Bulletin*, n. 19, 8 pp.

Hakodate, Japan, Marine Observatory (1979). *Report of the Sea Ice Observation in Okhotsk Sea and Adjacent Sea of Hokkaido (1979).* Marine Meteorological Rept. No. 35, pp. 32–39.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology. Springer-Verlag, New York, 397 pp.

Ishikawa, Masao (1970). Distribution of Pack Ice Field Off Hokkaido Observed with Sea Ice Radar Network (February–March, 1969). *Canada, Def. Res. Board, Trans.*, n. 105, 18 pp.

Kitani, K. (1973). An Oceanographic Study of the Okhotsk Sea: Particularly in Regard to Cold Waters. Japan, *Far Sea Fisheries Research Lab., Bull.*, n. 9, pp. 45–77.

La Violette, Paul E. (1967). *Temperature, Salinity, and Density of the World's Seas—Sea of Okhotsk.* U.S. Naval Oceanographic Office, NSTL, Mississippi, Rept. No. NOO-IR-67-88, 148 pp.

Miyagijima, Toshibumi (1969). Bathymetry of the Okhotsk Sea, Abstr. *Geol. Soc. Jap., J.*, v. 75, n. 2, pp. 85.

Moroshkin, K. V. (1968). *Water Masses of the Sea of Okhotsk.* Joint Publications Res. Serv., 10 January, 100 pp.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication, January.

Ogata, T. (1976). On the Relation Between the Sea Ice Generation and the Meteorological and Marine Phenomena in the Okhotsk Sea. *UMI to Sora*, v. 51(3–4), pp. 29–49, in Japanese.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Tabata, T., Y. Nohuguchi, and T. Saito (1980). Observed Sea Ice Thickness in the Northern Okhotsk Sea. *Low Temp. Sci. Ser. A*, (Japan), n. 39, pp. 153–158.

Tabata, Tadashi (1979). Distribution of Pack Ice Off Okhotsk Sea Coast of Hokkaido. *Low Temp. Sci., Ser. A*, Physical Sciences, Sapporo, Japan, n. 38, pp. 39–70.

U.S. Naval Oceanographic Office (1952). *Marine Geology of the Sea of Okhotsk.* NSTL, Mississippi, Rept. No. NOO-758, 260 pp.

U.S. Naval Oceanographic Office (1977). *Surface Currents. Sea of Okhotsk Including the Kuril Islands.* NSTL, Mississippi, Rept. No. NOO-SP-1402-NP-4, 48 pp.

Veselova, L. E. (1974). Short-Term Forecasting of Water Temperature on the Western Shore of Kamchatka. Dal'nevostochnyy Nauchno-Issledovatel'skiy, Gidrometeorologicheskiy Inst., Vladivostok, *Trudy*, n. 45, pp. 3–14.

Yakunin, L. P. (1974). Evaluation of Heat Balance Elements of the Okhotsk Sea with Consideration of the Ice Cover. Dal'nevostochnyy Nauchno-Issledovatel'skiy Gidrometeorologicheskiy Inst., Vladivostok, *Trudy*, n. 45, pp. 36–45.

East Siberian Sea

Ahlnas, K. and G. Wendler (1977). *Sea Ice Conditions in the Chukchi, Beaufort, East Siberian, and Northern Bering Seas during March 1973, 1974, and 1975 as seen from the NOSS-2, -3, and -4 Satellites.* University of Alaska, Fairbanks, pp. 83–104.

Car, Martial and William L. Gsell (1967). *Oceanographic Cruise Summary De Long Strait.* U.S. Naval Oceanographic Office, NSTL, Mississippi, Rept. No. NOO-IR-67-43, 22 pp.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Weather Service Command (1975). *Summary of Synoptic Meteorological Observations. Siberian Coastal Marine Areas, Volume 1. Area 1-Wrangel Island, Area 2-SW Chukchi Sea, Area 3-Anadryskiy Gulf, Area 4-Khatyrka, Area 5-Khatyrka 340S, Area 6-Karaginskiy Island, Area 7-Kronotskiy Peninsula.* Naval Weather Service Command, Monitor: 18, 455 pp.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Shpaikher, A. O. and Z. S. Iankina (1969). Peculiarities of Anomaly Development of Winter Hydrological Conditions in the East Siberian and Chukchi Seas. *Problemy Arkiki i Antarkiki*, Leningrad, n. 33, pp. 5–11.

Shpaykher, A. O. and E. P. Fedoroya (1976). Large-Scale Fluctuations in Salinity of the Siberian Shelf. USSR Gidrometorologicheskiy Nauchno-Issledovatel'skiy Tsentr USSR, Leningrad, *Trudy*, n. 319, pp. 42–62.

Labrador Sea

Anderson, Henry S. and Martin J. Moynihan (1971). *Oceanography of the Grand Banks Region and the Labrador Sea.* U. S. Coast Guard Rept. No. USCG-373-39, 326 pp.

Chough, S. K. (1978). *Morphology, Sedimentary Facies and Processes of the Northwest Atlantic Mid-Ocean Channel between 61 Degrees and 52 Degrees N, Labrador Sea.* McGill University, Montreal, Quebec, Canada, Doctoral.

Clarke, A. J.. D. S. Battisti. P. H. LeBlond, and T. R. Osborn (1981). Surface Circulation in the Western Labrador Sea. *Deep-Sea Res., Part A, Oceanogr. Res. Pap.* (Oxford), v. 28, n. 7, pp. 683–693.

Crange, R. G. (1979). Seasonal Variations of Sea Ice Extent in the Davis Strait-Labrador Sea Area and Relationships with Synoptic-Scale Atmospheric Circulation. *Arct. J. Arct. Inst. North Am.* (Montreal), v. 31, n. 4, pp. 434–447.

Egloff, J. and G. L. Johnson (1975). Morphology and Structure of the Southern Labrador Sea. *Can. J. Earth Sci.*, v. 12, n. 12, pp. 2111–2133.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Hyndman, R. D. (1973). Evolution of the Labrador Sea. *Can. J. Earth Sci.*, v. 10, n. 5, pp. 637–644.

Jezek, P. A. (1972). Physiography of the North Labrador Sea, Davis Strait and Southern Baffin Bay. *Mout. Sediments*, v. 8, n. 1, pp. 20–24.

Macnab, R. F. and S. P. Srivastava (1975). A Regional Geophysical Survey of the Labrador Sea. *Can. Geol. Surv.*, Pap. No. 75-1, Part A, pp. 177–179.

Mountain, D. G. (1978). Direct Current Measurements in the Labrador Current. *EOS, Trans. Am. Geophys. Union* (Washington, D.C.), v. 59, n. 12, pp. 1102–1103.

Moynihan, Martin J. and Henry S. Andersen (1971). *Oceanography of the Grand Banks Region and the Labrador Sea.* USCG Rept. No. USCG-373-48, 268 pp.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

Peery, Kenneth B. (1967). Geologic and Geophysical Observations in the Northern Labrador Sea. *Arctic*, v. 22, n. 1, pp. 56–68.

Rabinowitz, Phillip D. and Stephen L. Eittreim (1974). *Bottom Current Measurements in the Labrador Sea.* Lamont-Doherty Geol. Obs., Palisades, New York, Office of Naval Research, Rept. No. LDGO-2119, 9 pp.

Robe, R. Q., D. C. Maier, and W. E. Russell (1980). Long-Term Drift of Icebergs in Baffin Bay and the Labrador Sea: *Cold Regions Science and Technology*, Amsterdam, 1(3/4), pp. 183–193.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Swallow, J. C. and L. V. Worthington (1968). *Deep Currents in the Labrador Sea.* Woods Hole Ocean. Inst., Woods Hole, Massachusetts, Tech. Rept. No. WHOI-Ref-69-33; WHOI-Contrib-2234, 10 pp.

Tallwy, L. D. and M. S. McCartney (1980). Distribution and Circulation of Labrador Sea Water. *EOS, Trans. Am. Geophys. Union*, v. 61, n. 17, p. 252.

U. S. Naval Oceanographic Office (1978). *Surface Currents Northwest Atlantic Ocean and Labrador Sea.* NSTL, Mississippi, Rept. No. NOO-SP-1400-NA-4, 21 pp.

Vilks, G. (1980). *Postglacial Basin Sedimentation on Labrador Shelf.* Pap., Geol. Surv. Can. 78–28, 28 pp.

Baffin Bay/Davis Strait

Bacon, W. R. and R. N. Goodman (1980). *Weather Forecasting for Canadian Offshore Drilling in the Davis Strait.* Esso Resources Canada Ltd., Calgary, Alberta T2G 2B3, pp. 495–514, n. 80-07036.

Baker, Seymour R. and Gerald M. Friedman (1973). *Sedimentation in an Arctic Marine Environment; Baffin Bay between Greenland and the Canadian Arctic Archipelago.* Can. Geol. Surv., Pap. n. 71-23, pp. 471–498.

Blee, John J., Seymour R. Baker, and Gerald M. Friedman (1968). Sedimentological Survey of Baffin Bay. *Maritime Sediments*, v. 4, n. 1, pp. 4–6.

Ceres, Robert L. (1965). *The Seasonal Variation of Permanent Currents within Baffin Bay.* Naval Postgraduate School, Monterey, California, Master's Thesis, 2 pp.

Dunbar, Moira (1973). *Winter Regime of the North Water.* Defence Research Estab., Rept. No. DREO-691.

Dunbar, Moira (1972). *Increasing Severity of Ice Conditions in Baffin Bay and Davis Strait and Its Effect on the Extreme Limits of Ice.* Defence Research Est., Ottawa, Ontario, Rept. No. DREO-676, 7 pp.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Fleet Weather Facility (1976). *Eastern Arctic Sea Ice Analyses 1972–1975.* Rept. for Jan 72–Dec 75, Suitland, Maryland.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Hyndman, R. D., D. B. Clarke, H. Hume, J. Johnson, M. J. Keen, I. Park, and G. Pye (1970). Geophysical and Geological Studies in Baffin Bay and the Labrador Sea, abstr. *Marit. Sediments*, v. 6, n. 3, p. 145.

Jezek, Peter A. (1972). Physiography of the North Labrador Sea, Davis Strait and Southern Baffin Bay. *Marit. Sediments*, v. 8, n. 1, pp. 20–24.

Loeken, Olav H. (1973). *Bathymetric Observations Along the East Coast of Baffin Island; Submarine Moraines and Iceberg Distribution.* Can., Geol. Surv., Pap. n. 71-23, pp. 509–519.

Marlowe, James I. (1968). Unconsolidated Marine Sediments in Baffin Bay. *J. Sed. Petrology*, v. 38, n. 4, pp. 1065–1078.

Merklinger, H. M. (1975). Summertime Acoustic Conditions in Baffin Bay. *J. Acoust. Soc. of Am.*, v. 58, Supp. 1: S121, Fall.

Mitchell, P. A. (1979). *Eastern Arctic Area 15- and 30-Day Ice Forecasting Guide.* NSTL, Mississippi, Special Pub., Rept. No. NOO-SP-266.

Muench, Robin Davis (1971). *The Physical Oceanography of the Northern Baffin Bay Region.* Arctic Inst. of North Am., Rept. No. AINA-TR-7, 162 pp.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

Qamar, A. (1973). Seismicity of the Baffin Bay Region. *EOS, Trans. Am. Geophys. Union*, v. 54, n. 11, p. 1137.

Robe, R. Q., D. C. Maier, and W. E. Russell (1980). Long-Term Drift of Icebergs in Baffin Bay and the

Labrador Sea. *Cold Regions Sci. and Tech.*, Amsterdam 1(3/4), pp. 183–193.

Ross, D. I. and R. K. H. Falconer (1975). *Geological Studies of Baffin Bay, Davis Strait, and Adjacent Continental Margins.* Can. Geol. Surv., Pap. n. 75-1, Part A, pp. 181–183.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Srivastava, S. P. (1975). Geophysical Measurements in Labrador Sea and Davis Strait. *EOS, Trans. Am. Geophys. Union*, v. 56, n. 6, 381 pp.

Walmsley, J. L. (1966). *Ice Cover and Surface Heat Fluxes in Baffin Bay*. McGill University, Montreal, Arctic Meteorology Research Group, pub. in Meteorology, n. 84, October.

Bering Sea

Arsen'ev, V. S. (1965). Tsirkulyatsiya vod Beringova morya (Water Circulation in the Bering Sea). *Okeanologiches-kiye Issledovaniya*, 13:61-65. (Trans., 1966. U.S. Naval Oceanographic Office, NSTL, Mississippi).

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Hood, D. W. and E. J. Kelly (eds.) (1974). Oceanography of the Bering Sea with Emphasis on Renewable Resources. *International Symposium for Bering Sea Study*, 31 January–4 February 1972, Occasional Publication no. 2, Institute of Marine Science, University of Alaska, Fairbanks, 623 pp.

Hughes, F. W. (1972). *Circulation and Transport in the Western Bering Sea.* Ph.D. Thesis, University of Washington, Seattle, 151 pp.

Hughes, F. W., L. K. Coachman, and K. Aagaard (1974). Circulation, Transport, and Water Exchange in the Western Bering Sea. Chap. 3 in *Oceanography of the Bering Sea*, D. W. Hood and E. J. Kelly (eds.). Fairbanks, Institute of Marine Science, University of Alaska.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

Ohtani, K. (1973). Oceanographic Structure in the Bering Sea. *Memoirs of the Faculty of Fisheries, Hokkaido University*, v. 21, n. 1, pp. 65–106.

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Sayles, Myron A., Knut Aagaard, and L. K. Coachman. *Oceanographic Atlas of the Bering Sea Basin.* University of Washington Press, Seattle, and London.

Takenouti, Y. and D. W. Hood (1974). *Bering Sea Oceanography: An Update 1972–1974.* Fairbanks, Institute of Marine Science, University of Alaska, 292 pp.

U.S. Naval Oceanographic Office SP 3160-NP5, *Environmental Guide NP-5, Bering Sea*, NSTL, Mississippi. SECRET

Norwegian Sea

Batten, E. S. (1976). *Sea Ice Condition in the Norwegian, Barents, and White Seas.* Defense Advanced Research Projects Agency, R-1921-ARPA.

Fairbridge, R. W. (1966). *The Encyclopedia of Oceanography.* Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pennsylvania.

Herman, Y. (1974). *Marine Geology and Oceanography of the Arctic Seas.* Washington State University, Department of Geology, Springer-Verlag, New York, 397 pp.

Naval Arctic Manual (1970). ATP-17-(A) COMTAC Publication.

U.S. Naval Oceanographic Office (1978). *Surface Currents Norwegian and Barents Seas.* Reprinted 1980, NSTL, Mississippi, NOO SP 1400-NA2.

Naval Underwater Systems Center (1979). *Sound Speed Profiles for the Norwegian Sea.* New London, Connecticut, NUSC Technical Document 6035 (Second printing, April 1981).

Sater, J. E. (ed.) (1969). *The Arctic Basin.* Arctic Inst. of North Am., Washington, D.C.

Worthington, L. V. (1970). The Norwegian Sea as a Mediterranean Basin *Deep-Sea Research*, v. 17, pp. 77–84.

Appendix O: World Meteorological Organization sea ice classification

A review of the World Meteorological Organization (WMO) ice classification scheme follows. Each category relevant is described in order of increasing ice thickness. Thickness data and distinguishing characteristics are summarized in Table 1. Figures 1–13 show aerial photographs of each ice type.

Open water

Ice-free areas (open ocean, polynyas, leads, and interstices between ice floes) constitute open water. Ice thickness here is zero and albedo is lower than that of any other Arctic surface. Open water can occur anywhere in the Arctic in any season. Open water bodies vary greatly in size and area. Small, confined areas of open water are common between adjacent floes during summer months (Fig. 1). Such areas of open water commonly are not completely ice free and typically contain isolated chunks of floating ice that vary in size from centimeters to tens of meters. Leads are linear bodies of open water that form when fractures in the pack widen in response to tension (Fig. 2). Lead width ranges from meters to kilometers. Polynyas are enclosed nonlinear openings within the pack ice. Although the term polynya is usually reserved for predominantly ice-free (water) openings, polynyas typically include small amounts of brash ice or may be partially covered with new ice, nilas, or young ice. Some polynyas occur in the same position every year and are referred to in the literature as recurring polynyas.

New ice

During winter months (October through April), ice formation begins almost as soon as chilled water is exposed to air at subfreezing temperatures. Open water observed in winter scenes thus commonly includes suspended ice

Table 1.

Ice Type	Thickness*	Gray Tone	Deformational Features
Open Water	0 cm	black	
New Ice			
frazil	0 cm	black	unconsolidated
slush	0–50 cm	very dark gray to gray	unconsolidated
shuga	0–50 cm	dark gray to gray	unconsolidated
grease ice	0–100 cm	dark gray to gray	unconsolidated
Nilas			
dark nilas	0–5 cm	very dark gray	rafts
light nilas	5–10 cm	dark gray to gray	rafts
Young Ice			
gray ice	10–15 cm	gray to light gray	rafts
gray-white ice	15–30 cm	light gray to almost white	rafts or ridges
First-year ice			
thin	30–70 cm	white	ridges
medium	70–120 cm	white	ridges
thick	120–200 cm	white	ridges
Old ice			
second-year ice	2–4 cm	white	ridges
multiyear ice	2–4 cm	white	ridges, hummocks

*Thickness ranges shown are those established by the World Meteorological Organization (1970) ice classification scheme.

spicules and disks (frazil) that represent the initial stage of ice-cover formation. New ice consists of unconsolidated accumulations of frazil, commonly agglomerated as slush in spongy clumps, streamers, and tadpoles (Dunbar and Weeks, 1975; Fig. 3). When light winds push dispersed clumps of frazil into a concentrated mass, a soupy, unconsolidated layer of grease ice up to a meter thick forms on the sea surface (Weeks and Ackley, 1982). Water content of most types of new ice typically is greater than 60% by volume (Martin and Kaufmann, 1982). This high water content makes dispersed frazil and thin accumulations of grease ice indistinguishable from open water in most vertical aerial photographs. Streamers and tadpoles of slush and thick accumulations of grease ice display higher albedo than surrounding water, however, and commonly are visible in winter scenes of open water (Fig. 3).

Nilas

Nilas is a thin, elastic crust of ice, less than 10 cm thick, that bends under the influence of waves and swell. Under compression, nilas rafts (Fig. 3), sometimes in fingers (Fig. 4) rather than forming ridges that are common in most thicker forms of ice (gray-white ice, first-year ice, and old ice). Nilas will not sustain snow cover, probably because of a combination of surface brine and insufficient thermal insulation against the near-melting temperature of underlying sea water. Nilas commonly occurs adjacent to open water (Fig. 3) and is the first consolidated sheet of ice to form. Nilas is divided into two categories, dark nilas and light nilas, on the basis of thickness and albedo. Dark nilas (Fig. 5) is less than 5 cm thick, is very dark in tone (nearly as dark as open water), and is the thinnest consolidated type of ice. Light nilas (Fig. 6) ranges in thickness from 5 to 10 cm and is lighter in tone than dark nilas.

Young ice

Young ice ranges in thickness from 10 to 30 cm, is less elastic than nilas, and breaks under swell and wave action rather than bending as nilas does. It may raft or ridge under compression, depending on thickness (compare Figs. 7 and 8). Young ice is divided into two categories, gray ice and gray-white ice, based on thickness, albedo, and ability to sustain snow cover. Gray ice (Figs. 7 and 8) ranges in thickness from 10 to 15 cm, has a higher albedo than nilas, generally will not sustain snow cover, and typically rafts rather than forming ridges under compression. Gray ice appears gray in aerial photographs. Gray-white ice (Fig. 9) ranges 15–30 cm in thickness, has a higher albedo than gray ice (but slightly lower albedo than first-year ice), and sustains snow cover. Under compressive stress, gray-white ice either rafts or form ridges. When snow cover is present, discrimination between gray-white ice and thin first-year ice is difficult if deformational features (rafting, ridges) are absent.

First-year ice

First-year ice is ice of not more than one winter's growth that ranges in thickness from 30 cm to 2 m. First-year ice has a high albedo and sustains snow cover. Under compressive stress it forms ridges that commonly appear fresh and sharp (Figs. 10 and 11). Undeformed ice between ridges is smooth. Drifting snow supplies whatever surficial texture is present.

At the onset of freeze-up in the fall (typically September or October), first-year ice that formed during the previous winter and survived the last summer melt is, by definition, second-year ice. As winter progresses, young ice forms and thickens, and the current winter's first-year ice is created. If this ice is not deformed into a ridge, it continues to thicken throughout the winter. By the onset of spring melt (typically May for the central Arctic), first-year ice that began growing in October has attained thicknesses of up to 2 m (Fig. 11), although in local, undisturbed low-salinity waters it can exceed this thickness. Not all first-year ice attains a thickness of 2 m. First-year ice that began growing late in the season will, of course, be thinner (Fig. 10). The actual thickness of first-year ice thus is difficult to determine from photographs in all but the earliest stages of growth.

Old ice

Old ice is ice that has survived at least one summer's melt. At the beginning of winter, old ice may be less than 2 m thick due to the effect of summer melt. By winter's end, old ice has grown to a total thickness that commonly ranges 2–4 m. Under compressive stress old ice forms ridges. Although new ridges appear blocky (Figs. 10 and 11), relict ridges that survive from past years are rounded and form hummocks of lower relief (Fig. 12). Meltponds that formed in summer months have frozen and are present between ridges and hummocks. Old ice sustains snow cover and displays high albedo similar to that of first-year ice as a result. Old ice is distinguished from first-year ice primarily by differences in roughness of the ice surface that are created by increased snow cover, relict ridges, and meltpond and drainage patterns.

Icebergs

Icebergs are massive chunks of fresh-water ice that break (calve) from the terminus of a glacier or ice shelf. They are distinguished from floes of sea ice by their size, higher freeboard (typically greater than 5 m for large icebergs (WMO, 1970)), high relief and, in some cases, their irregular shape.

References

WMO (1970). *WMO Sea-Ice Nomenclatures.* Secretariat of the World Meteorological Organization, Geneva, Switzerland, 147 pp.

Dunbar, M. and W. F. Weeks (1975). *Interpretation of Young Ice Forms in the Gulf of St. Lawrence Using Side-Looking Airborne Radar and Infrared Imagery*. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, CRREL Research Report 337, 41 pp.

Weeks, W. F. and S. F. Ackley (1982). *The Growth, Structure, and Properties of Sea Ice*. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, CRREL Monograph 82-1, 136 pp.

Martin, S. and R. P. Kauffman (1982). A Field and Laboratory Study of Wave Damping by Grease Ice. *Journal of Geophysical Research*, v. 27, n. 96, pp. 283–313.

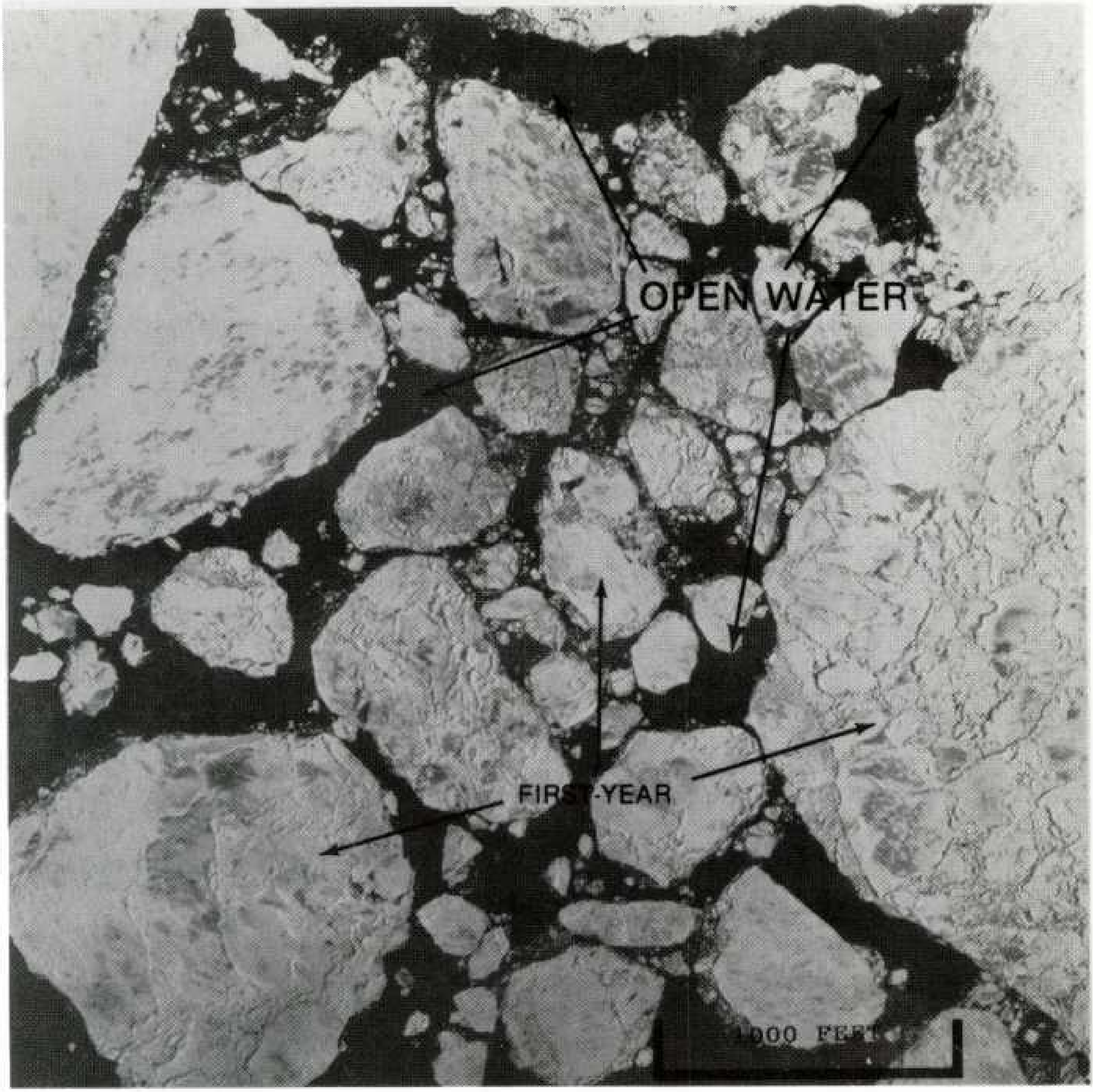


Figure O.1. Open water fills voids between melting floes of first-year ice in a loose April pack in Baffin Bay. Gaps between floes indicate that the pack is not under compression. Altitude is 3000 ft.

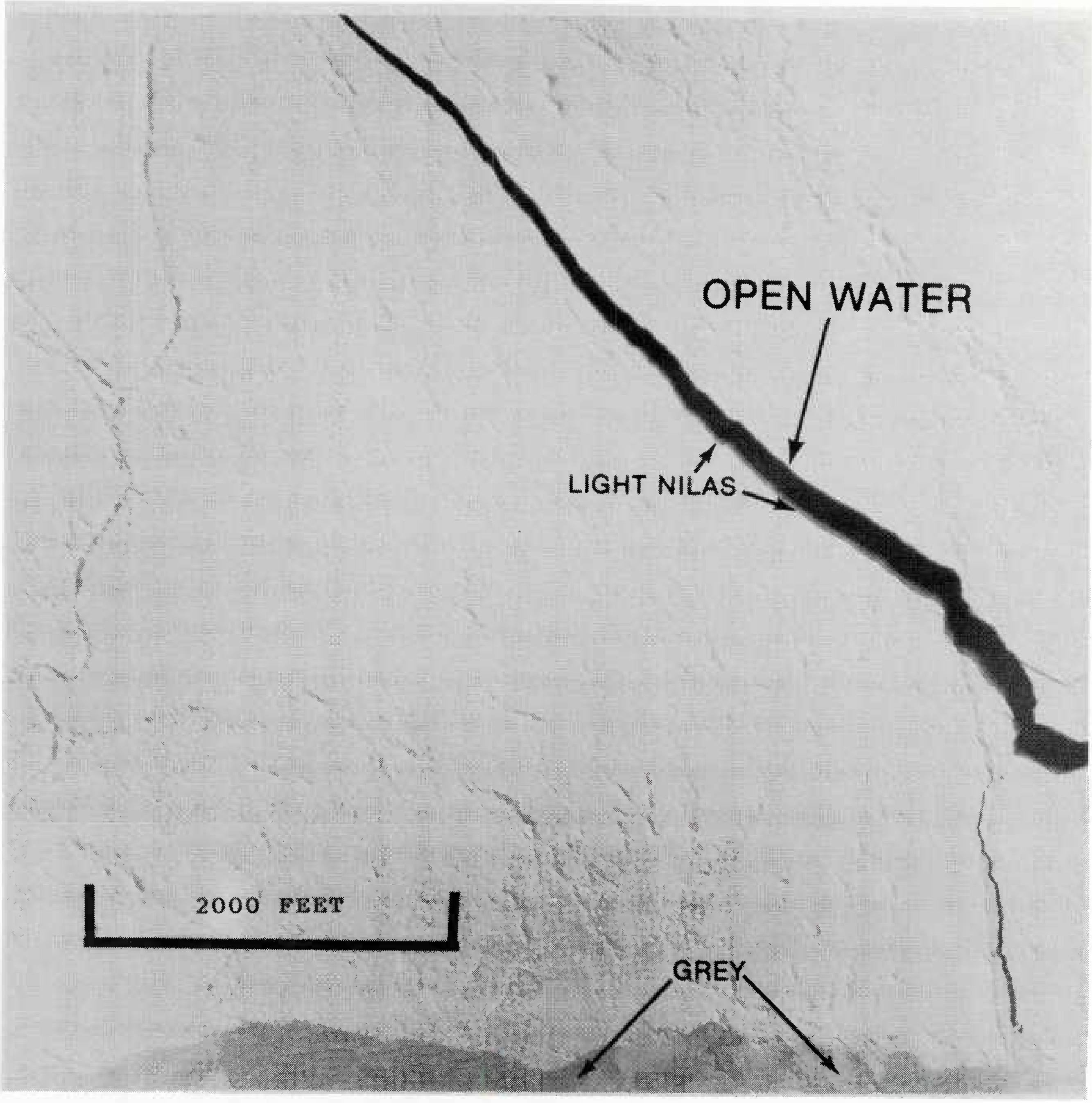


Figure O.2. Open water exposed in a small lead formed in first-year ice. Narrow band of nilas along lower edge of lead indicates that water exposed in the lead has begun to freeze. Gray ice along bottom of image marks a frozen lead that formed in a previous episode of rifting. Altitude is 5000 ft.

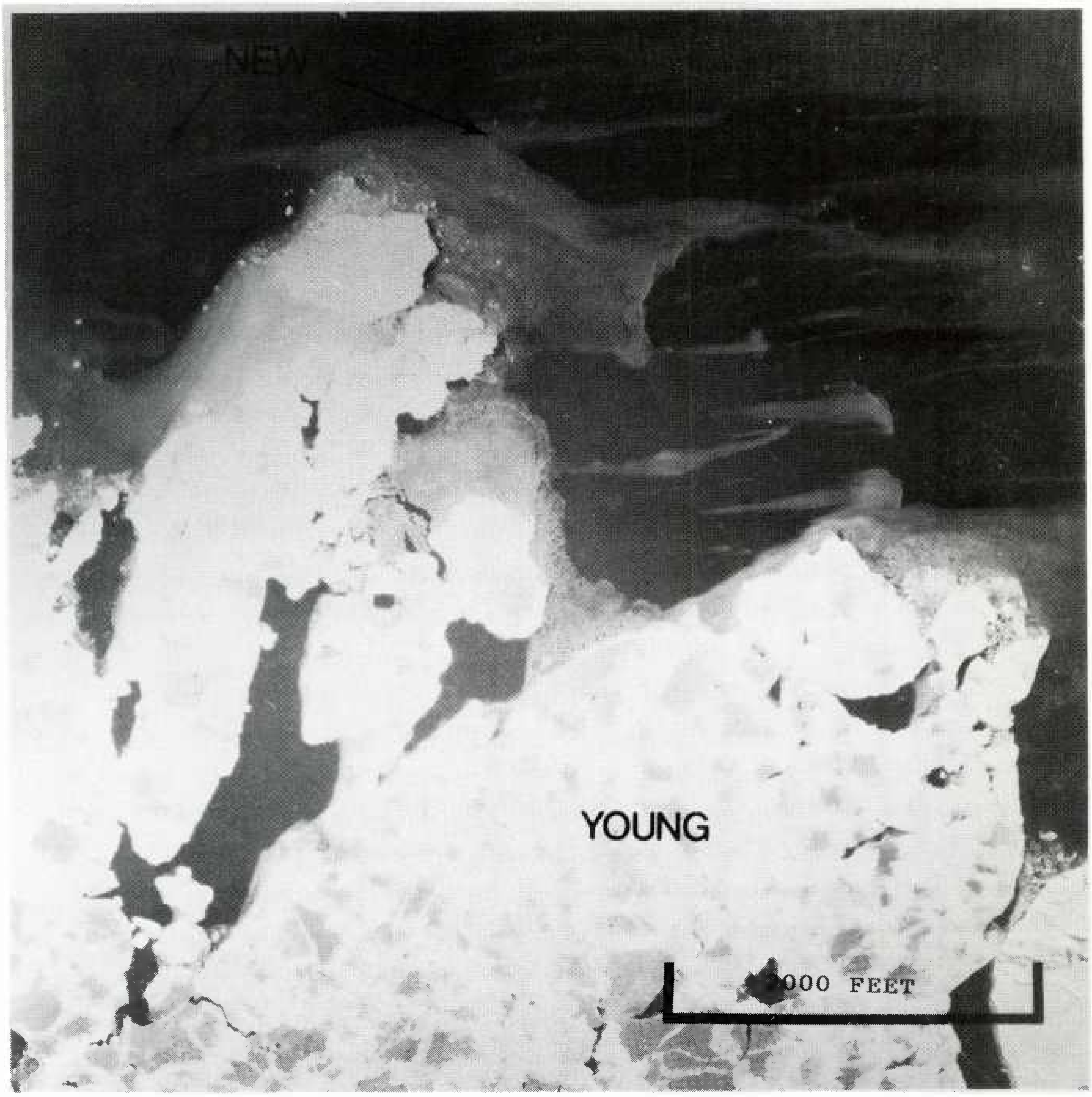


Figure O.3. Spongy clumps of slush form stringers and tadpoles of new ice that are aligned parallel to prevailing winds (top of image). The unconsolidated character of new ice is evidenced by the presence of ocean waves and ripples in streamers, tadpoles, and accumulations of grease ice. Waves are not evident in adjacent nilas and young ice which, though of similar albedo, are consolidated. Altitude is 5000 ft.

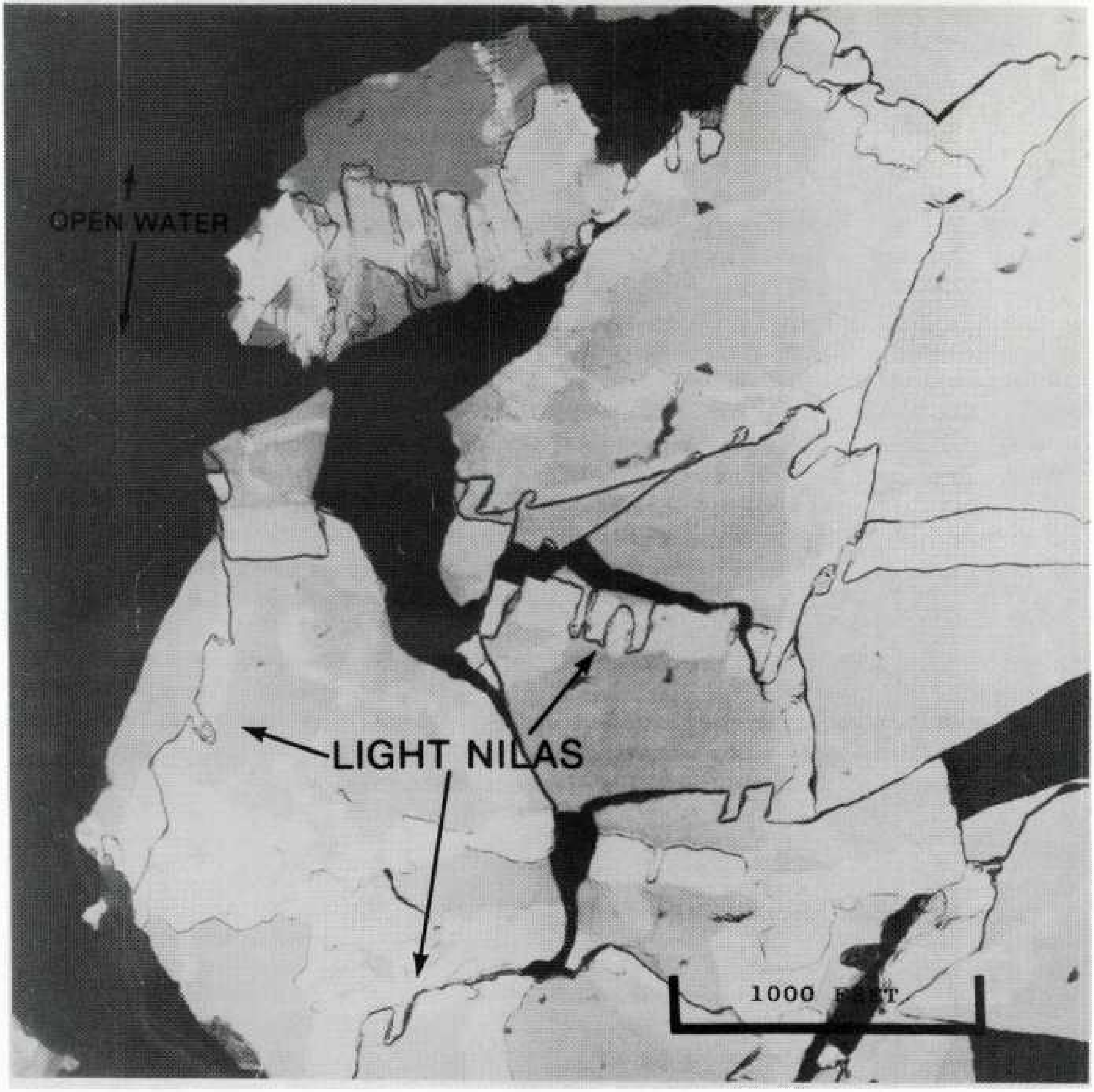


Figure O.4. Nilas rafted in fingers. Rafts form when one piece of ice overrides another in response to compression. Finger rafting occurs when alternating sections of one ice sheet override and underride an adjacent ice sheet at the juncture between the two ice sheets. Finger rafting is common in nilas and gray ice. Altitude is 3000 ft.

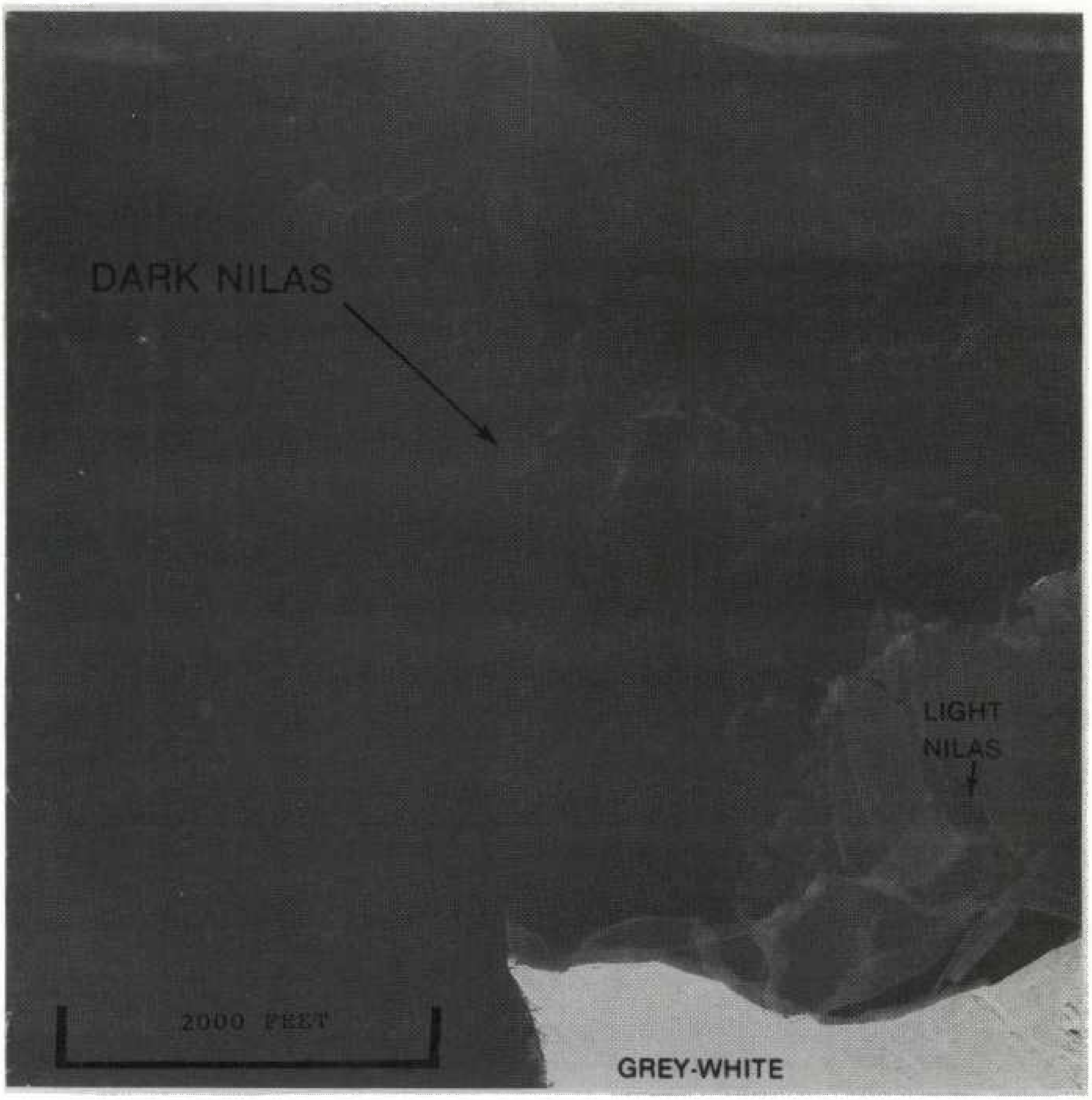


Figure O.5. Dark nilas forms a sheet of ice less than 5 cm thick across most of this image. Its presence is indicated best by rafts that are of higher albedo than the darker unrafted dark nilas. Light nilas and gray-white ice are present in the lower right corner of the image. Altitude is 5000 ft.

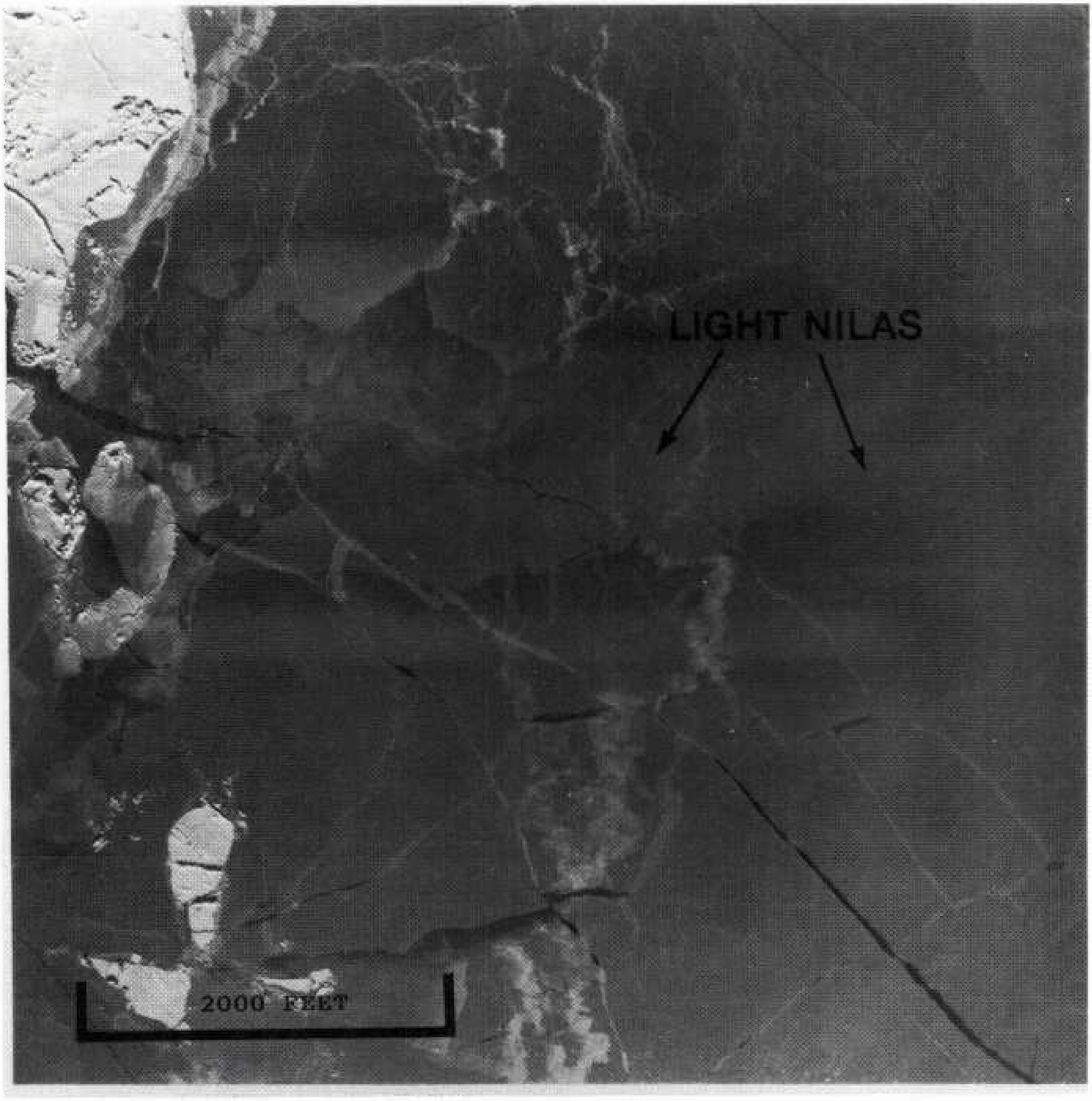


Figure O.6. Light nilas between 5 and 10 cm thick covers most of this image. Thickness variation and rafting create differences in albedo from point to point. Fractures and rafts indicate a consolidated ice sheet. Altitude is 5000 ft.

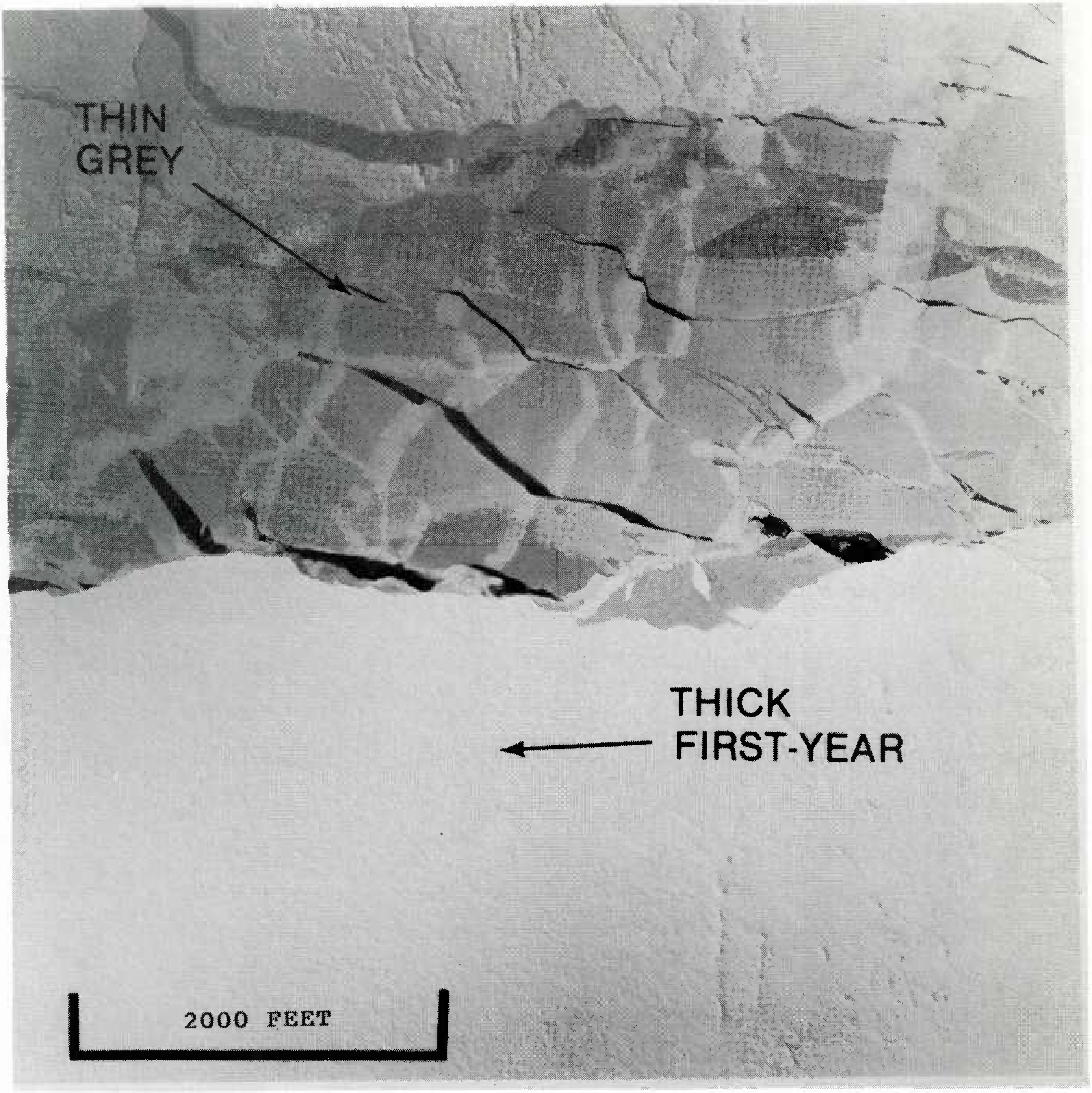


Figure O.7. Thin, rafted gray ice approximately 10 cm thick fills a lead in thick first-year ice. Cracks in gray ice expose water, now frozen in some instances to light and dark nilas. Altitude is 5000 ft.

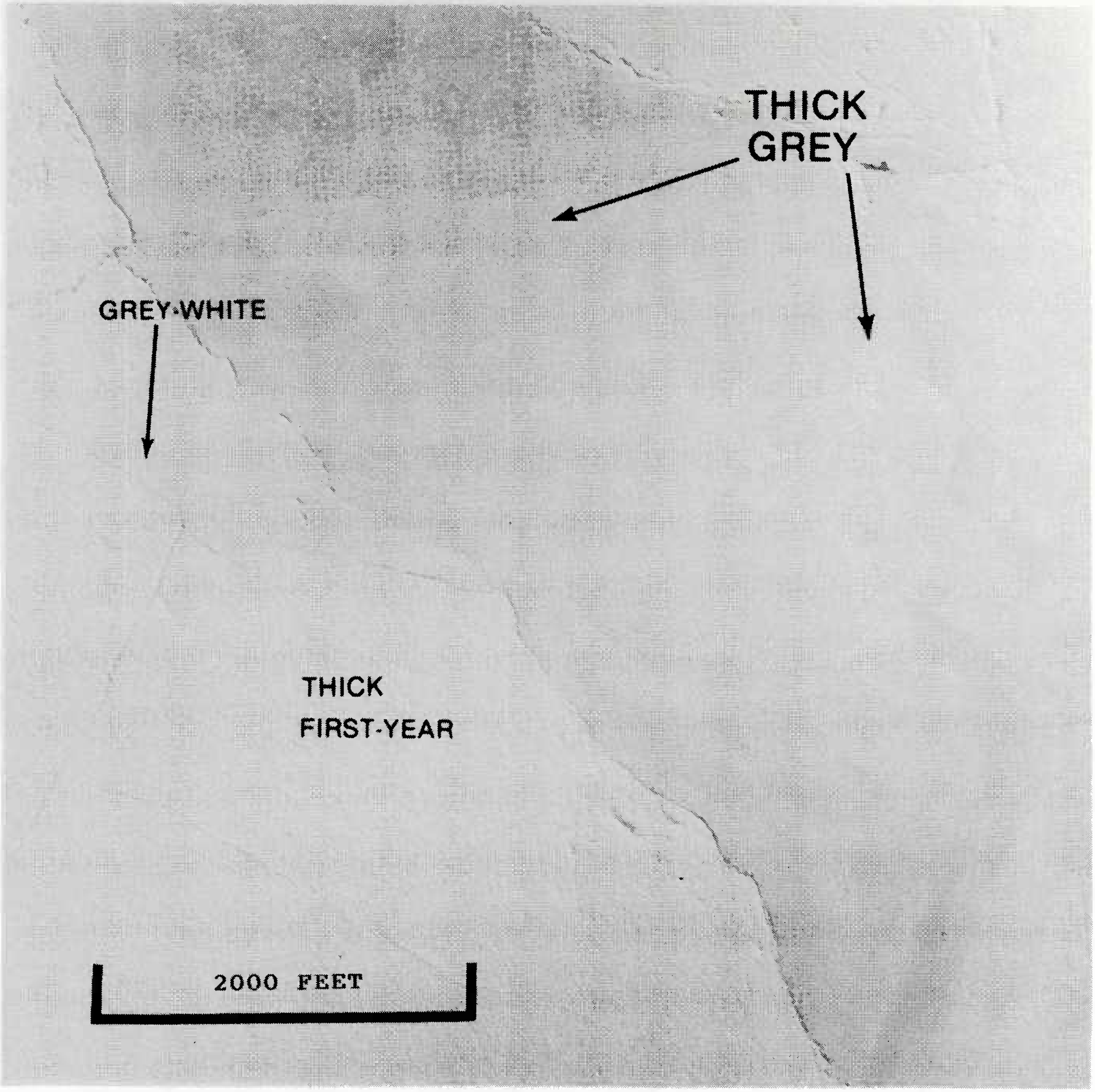


Figure O.8. Thick gray ice approximately 15 cm thick fills a lead in thick first-year ice. Gray ice here is both rafted and ridged. Gray-white ice fills an older, secondary lead at the left edge of the image. Altitude is 5000 ft.

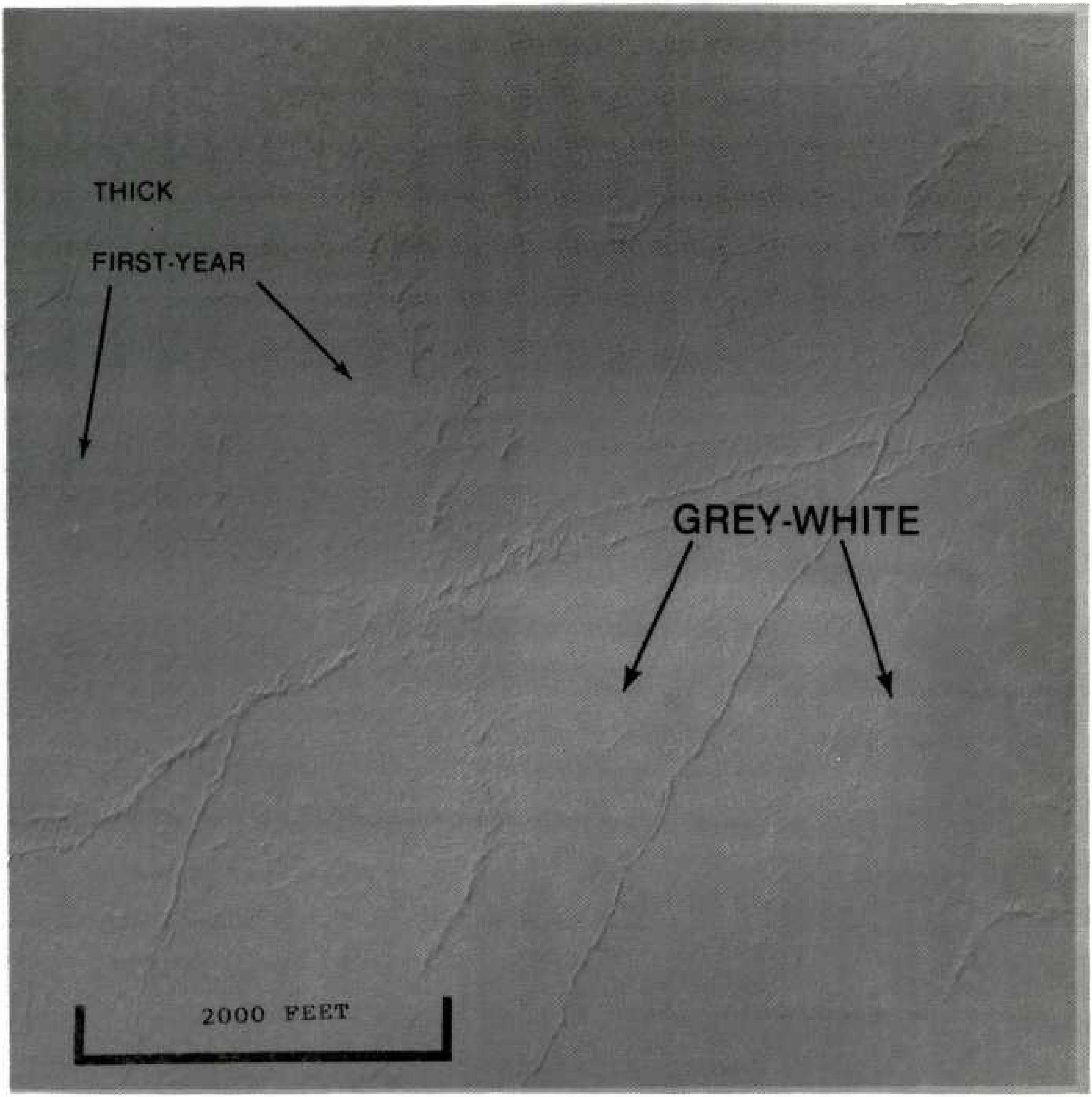


Figure O.9. Gray-white ice 15 to 30 cm thick in a field of thick first-year ice. Here gray-white ice sustains snow and forms sharp ridges. The gray-white tone and smooth surface of gray-white ice distinguish it from adjacent first-year ice. Altitude is 5000 ft.

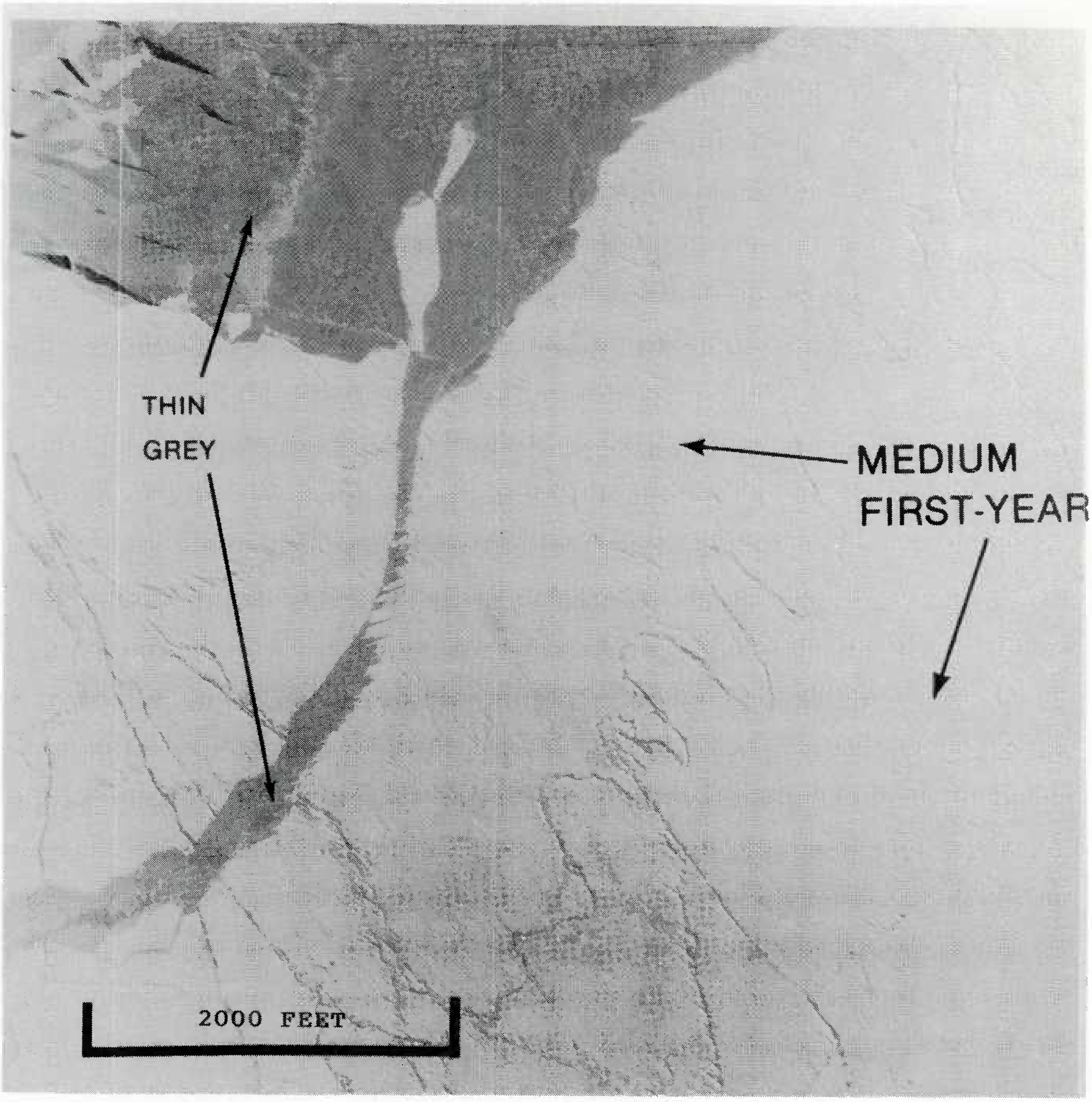


Figure O.10. Medium first-year ice covers the right half of this image. Rafted thin gray ice is present in upper left corner of image and fills an arcuate lead in the left half of the image. Note meandering pattern of ridges in first-year ice that mimics finger-raft patterns typical of nilas. Altitude is 5000 ft.

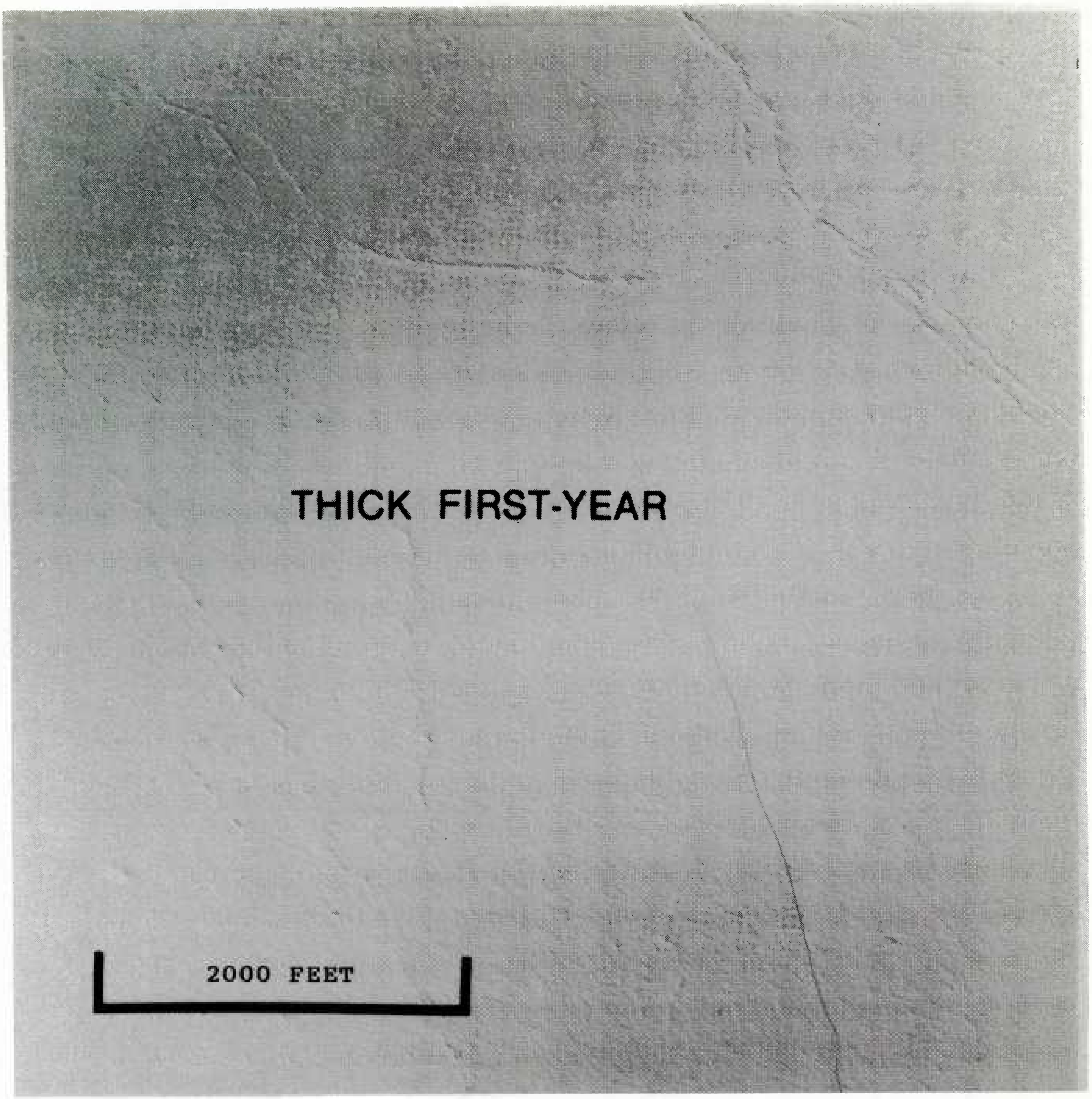


Figure O.11. Thick first-year ice. Extensive snow cover produces a rougher surface than that typical of thinner examples of first-year ice (Fig. 10). Moreover, some ridges are less blocky and are more subdued in appearance than ridges on thinner ice. Altitude is 5000 ft.

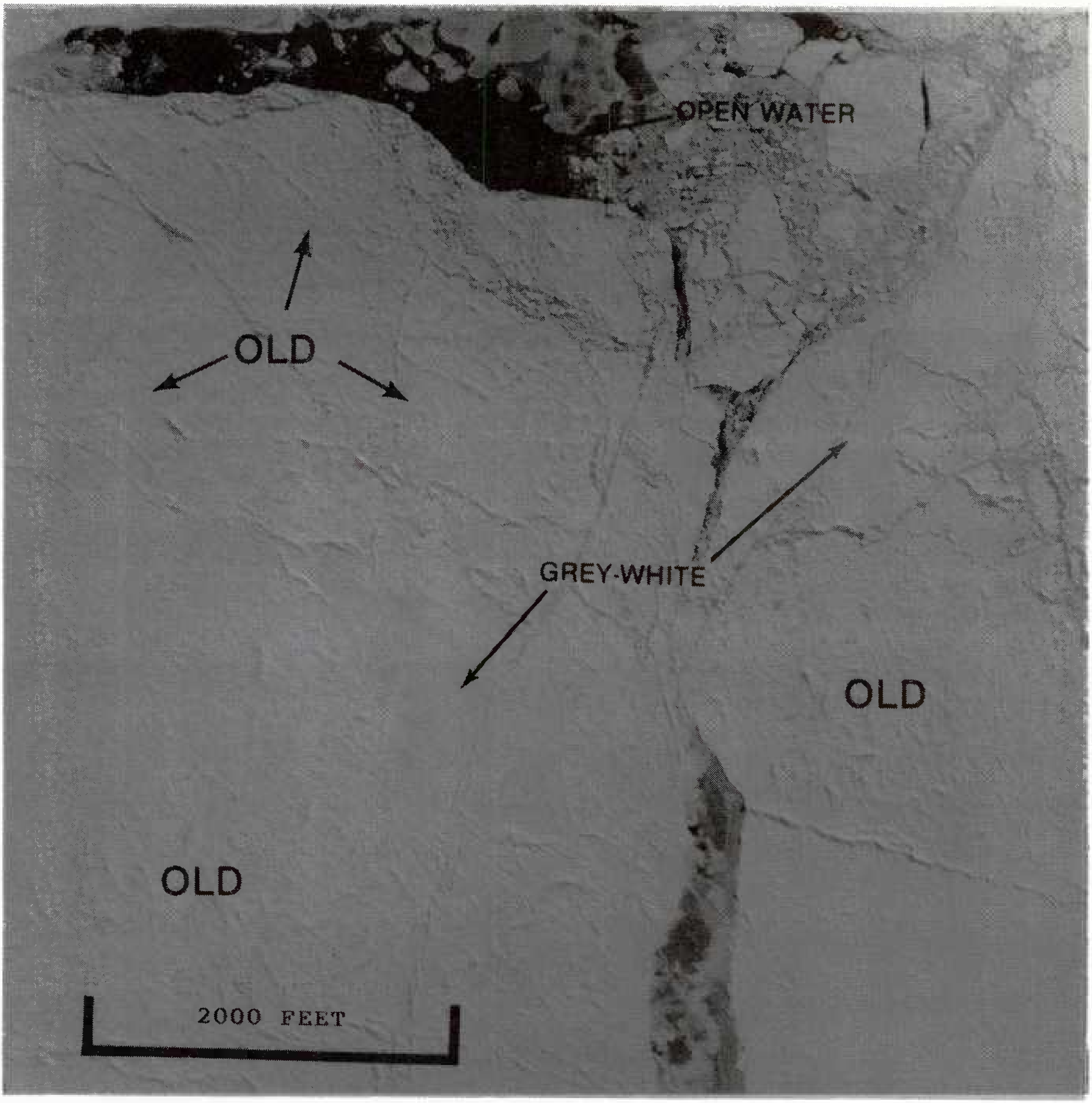


Figure O.12. Old ice floes are set in a matrix of gray-white ice, light nilas, and open water. Relict ridges and drainage structures roughen old ice surfaces. New ridges, though sharp and blocky, vary in height and width along their length. Altitude is 5000 ft.

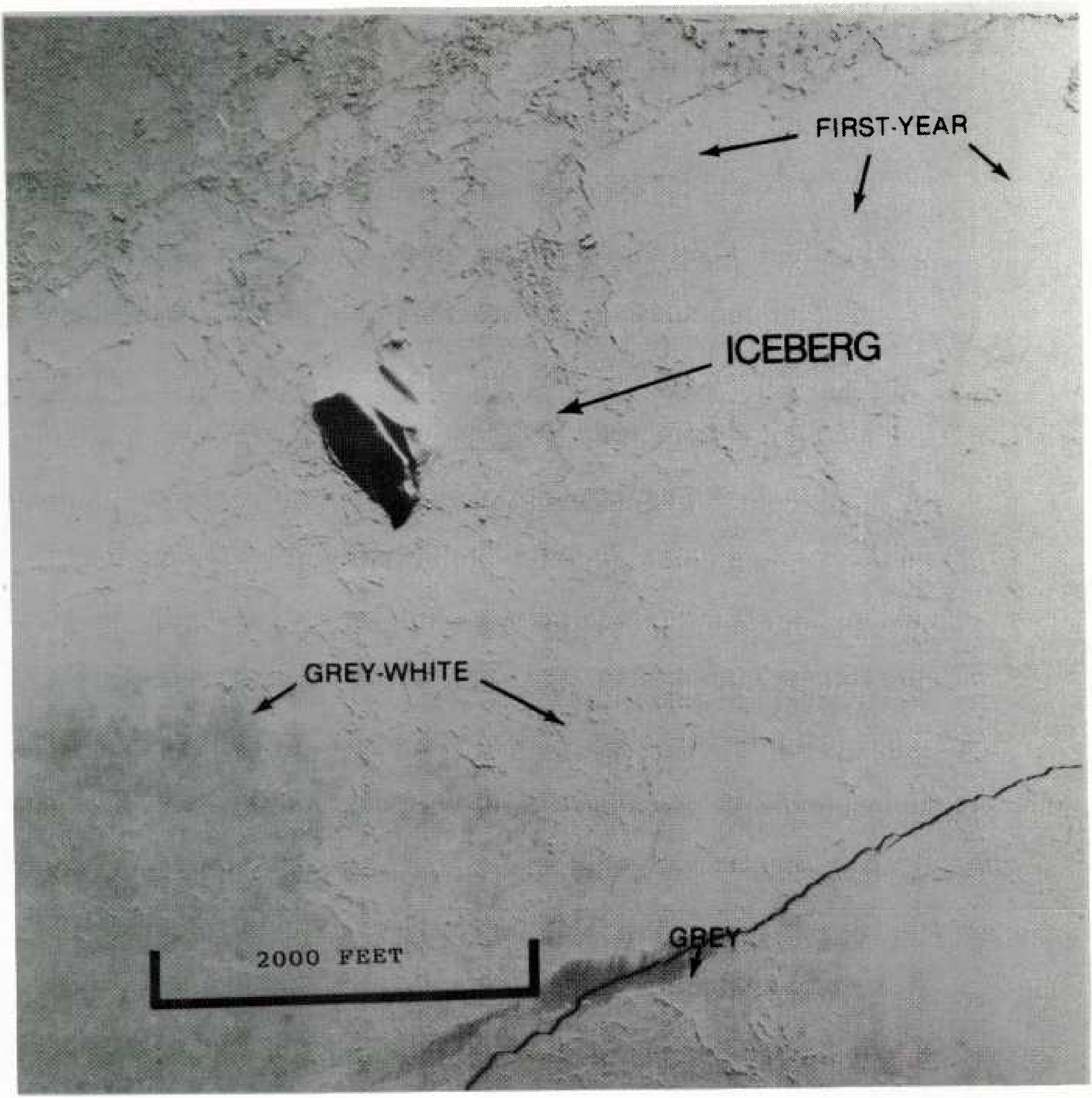


Figure O.13. Iceberg frozen in a closed pack of first-year ice and gray-white ice in Baffin Bay. Altitude is 5000 ft.