2. PHYSICAL CHARACTERISTICS OF THE ARCTIC

Since the time of the ancient Greeks, scholars have been intrigued by the similarities and the differences between the Earth's north and south polar regions. While both are cold and have abundant ice, when stripped of water and ice they possess striking dissimilarities. In the south appears a huge continent with an area of nearly 5 million sq mi (14 million sq km). But in the north just the opposite occurs, the huge Arctic Ocean Basin with an area nearly as great. This section provides an opportunity to examine the physical characteristics of the high north.

2.1 Submarine Topography of the Arctic Basin

Figure 2-1 shows the bathymetry of the Arctic Ocean. It illustrates a number of features that determine the nature of the ice distribution and circulation. The prominent *Lomonosov Ridge* splits the region into two major subbasins: the Eurasian and Amerasian. It stretches from the Laptev Sea to Ellesmere Island. The Eurasian Basin is bounded to the south by Greenland, Spitsbergen, and the Taimyr Peninsula. It extends to a maximum depth in excess of 13,780 ft (4,200 m). Large amounts of water can obviously be exchanged between this basin and the Atlantic Ocean by way of the Greenland and Norwegian Seas. The water from the Arctic Ocean is cold and fresher while the North Atlantic Current provides warmer and more saline water to mix in the basin. Note that the continental shelf surrounding the Eurasian Basin is very narrow, averaging only 23 to 58 mi (37–93 km).

In contrast, the other Arctic Ocean basin, the Amerasian, has a very broad continental shelf, up to 342 mi (550 km) across. The Amerasian Basin has an average depth of 12,960 ft (3,750 m) and extends from Ellesmere Island to the East Siberian Sea. It includes the Canadian Basin (Beaufort Sea), which is connected with the Pacific Ocean by the narrow (40 mi or 64 km) and shallow (148 ft or 45 m) Bering Strait.

The marginal seas, which make up the edges of the Arctic Ocean over the continental shelf, occupy 35 percent of the entire ocean area but account for only 2 percent of the volume (large areal extent but relatively shallow), indicating great water depth in the two major basins. Most of the rivers supplying the Arctic Ocean flow into the shallow seas and make the ocean fresher in spring and subject it to more evaporation because of the

Figure 2-1. Bathymetry of the Arctic Ocean (Sater et al., 1971).

depth-to-exposed-area ratio. Through the Bering Strait only near-surface water flows into the Arctic Ocean. In this area the Arctic Ocean has Pacific Ocean characteristics.

Furthermore, the large canyons leading into the Arctic have an influence on the nature of the water. These act as pathways for egress of water from warmer oceans into the shallow Arctic seas and mixing can alter the state of water and ice.

As noted before, the Arctic Ocean is almost completely landlocked with the exception of a small number of restricted openings, generally of small depth, which act more as sills than as open passages for the circulation of the water. Some examples are the Bering Strait,

the Nares Strait (9 mi or 15 km wide, 820 ft or 250 m deep) between Ellesmere Island and Greenland, and the numerous narrow channels throughout North America. The only large communication pathway is the Fram Strait at the top of the North Atlantic Ocean between Spitsbergen and Greenland, where a deep trench (deeper than 6,562 ft or 2,000 m for more than 155 mi or 250 km) allows warm Atlantic waters to flow freely into the Arctic Basin. Simultaneously, a powerful surface countercurrent of drifting ice and cold water comes out of the polar sea, paralleled by an important deep overflow of Arctic waters that cascades over sills into the North Atlantic on both sides of Iceland. On the eastern side, despite the presence of a large unrestricted passage, the shallow continental platform of the Barents Sea prevents a large exchange with the North Atlantic; this particular inflow plays only a secondary role.

The overall transfer through the Fram Strait is enormous, representing more than 35 million cu ft (7 million cu m) per second. It brings into the Arctic Ocean huge amounts of warm, saline water, which, sinking to middepths, drive permanent transpolar currents and contribute to giving to the whole Arctic Basin a role of heat radiator in the heart of the northern cold territories. This powerful Atlantic inflow, however, coming from the direction of offshore America and western Europe, threatens to become a source of possible pollution.

Finally, the geometry of the Arctic Ocean provokes the convergence of the circumpolar runoffs coming from adjacent continents: from Siberia and North America powerful rivers carry hundreds of megatons of fresh water into the Arctic Basin. At the present rate, the Yenisei, Ob, Lena, Kolyma, and Mackenzie Rivers, draining a continental area of more than 4 million sq mi (10 million sq km), have a runoff equivalent to five times the Mississippi River and almost half the Amazon. This fresh water, spreading at the surface of the heavier saline marine water, prevents normal convection and reduces vertical mixing; thus it seriously impedes biological development, a situation that is quite contrary to that of the Antarctic Ocean. Runoff brings also a great mass of natural sediments, as well as organic material and undesirable chemicals from midlatitude fallout on the drainage basins of circumpolar rivers. Those pollutants tend to remain in the surface freshwater; they are distributed all around the Arctic Basin by the "Transpolar Drift" from northern Siberia to the Fram Strait, and relayed by the Pacific Gyre north of North America, so that all circum-Arctic countries receive their share.

2.2 The Arctic Seas

The Arctic Ocean is the world's smallest ocean with an area of 5 million sq mi (14 million sq km). Relatively little is known about the Arctic Ocean because of its limited access by ships and its isolation from population centers. Open water areas of the Arctic consist primarily of leads and polynyi that figure significantly in the Arctic heat budget. These openings are characterized by water vapor evaporation to the air at a rate two orders of magnitude greater than evaporation from ice. Tides vary over the Arctic Ocean from as much as an inch or two (2–5 cm) in the Beaufort Sea to as much as 40 ft ($\approx$ 12 m) in some embayments of the Canadian Archipelago (Lopez, 1986).

Arctic Ocean water consists of three different water masses. The surface layer, *Arctic water,* is generally near the freezing point but relatively dilute with salinities around

28–32 parts per thousand (ppt). Below about 165 ft (50 m) the salinity increases rapidly with depth (Fig. 2-2). Because temperature has less effect on density than salinity in cold Arctic water, however, the vertical profiles of salinity and density are virtually parallel.

Immediately below the Arctic water is the *Atlantic layer* ranging from a depth of 650 to 3,000 ft (200–900 m). This layer has temperatures near freezing, often reaching 37 °F (3 °C). The salinity in this layer is quite uniform at near 35 ppt. This layer is a major heat source within the Arctic Ocean.

Finally, the *bottom water* makes up the deepest layer. Temperature and salinity are both quite uniform in this layer at about 31 °F (−0.5 °C) and 34.95 ppt. It constitutes nearly 60 percent of the water volume in the Arctic Basin.

The following subsection discusses the salient features of each of the major Arctic seas. Boundaries of the various seas are shown in Fig. 2-3.

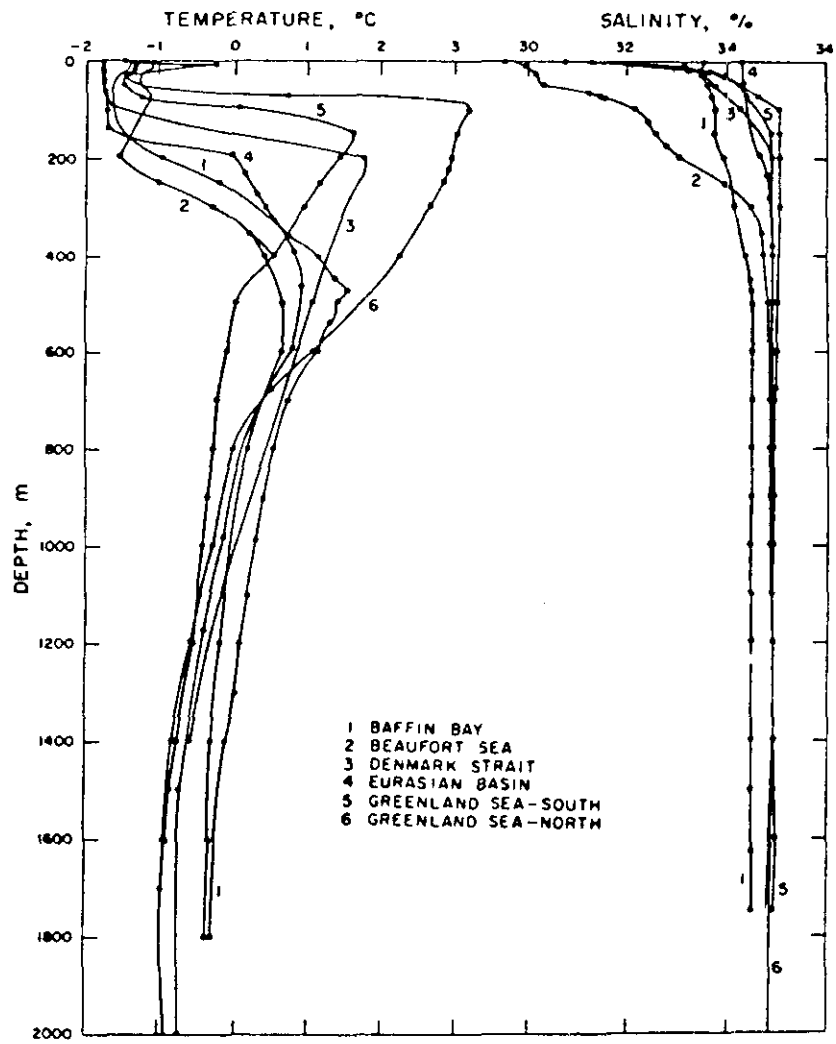

Figure 2-2. Vertical Profiles of Temperature and Salinity at Six Arctic Locations (Welsh et al., 1986).

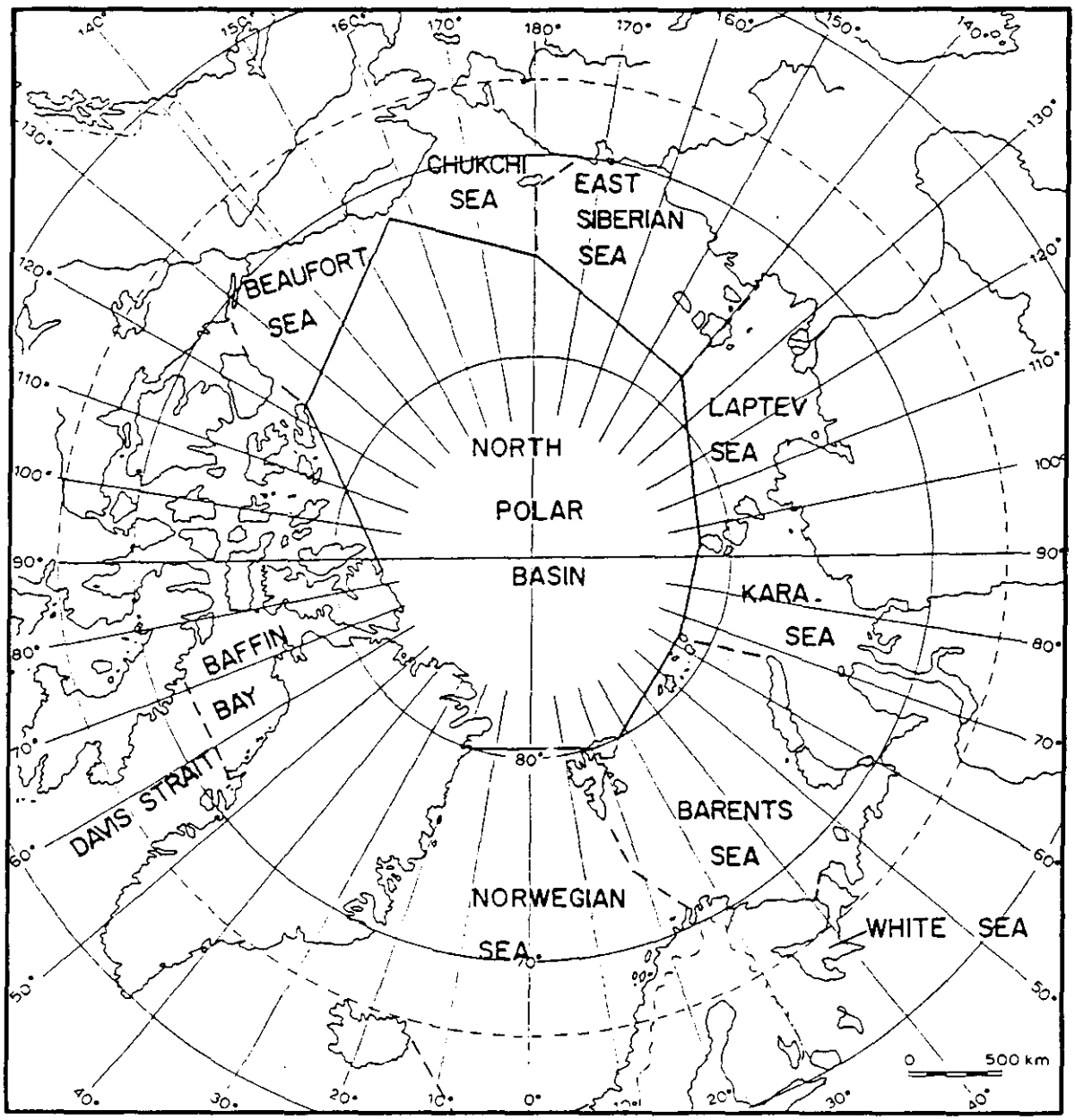

Figure 2-3. The Arctic Seas (Orvig, 1970).

Note (applicable to subsections 2.21 through 2.2.10):

(1) Quoted wind speeds and wave heights are climatological values. *Maximum* winds usually occur with synoptic storm systems or with polar lows and are known to exceed 60 kt (30 m/s).

(2) Reference is made to polar and subarctic climates. In general, polar climate refers to the air temperature being less than 50 °F (10 °C) in the warmest months, whereas in a subarctic climate the temperature in the warmest months is above 50 °F (10 °C).

(3) Extensive use was made of the material included in *A Compendium of Arctic Environmental Information* (Welsh, 1986). This book is very useful for those working in the Arctic.

2.2.1 Beaufort Sea

The Beaufort Sea's surface Arctic water is about 330 ft (100 m) thick and is the coldest of all the water masses. Furthermore, it is the only layer that undergoes significant seasonal changes in temperature and salinity. These changes are in response to the freezing and thawing of the pack ice, plus the freezing and thawing of rivers in coastal areas.

The Atlantic layer in the case of the Beaufort Sea is overlain by Pacific water, which enters through the Bering Strait. The Pacific water is, of course, relatively warmer than the other layers.

The circulation of the Beaufort Sea is dominated by the clockwise Beaufort Gyre that covers the entire Canadian and Beaufort Deeps. The currents flow at a rate of 1–2 n mi/day (2–4 km/day) but may be highly variable along coasts and may even reverse direction depending on local surface winds and/or synoptic pattern winds.

The sea ice of the Beaufort Sea is packed up against the Canadian and Alaskan coasts due to the gyre. Thus, navigation and observations are restricted in all seasons except late summer. Seas are normally less than 3 ft (1 m) due to the extensive ice cover but may reach 5 ft (1.5 m) for brief periods in late summer. They can reach 20 ft (6 m) in fall and spring with severe storm events.

The climate of the Beaufort Sea can be summarized as follows: Summer temperatures range from −15 °F to 54 °F (−26 °C to −12 °C); in winter the range is −35 °F to 1 °F (−37 °C to −17 °C). The record low temperature is −72 °F (−58 °C), and the temperature may be less than −25 °F (−31.5 °C) 85 days/year. Winds may exceed 21 kt (11 m/s) 55 days/year.

2.2.2 Baffin Bay and Davis Strait

Baffin Bay at its maximum depth reaches 6,600 ft (2,012 m), making it one of the deeper bodies of Arctic water. In this region the cold Arctic waters mix with the warmer Atlantic Ocean. Thus, the variations in surface characteristics are great in their response to seasonal and migratory storm conditions. The surface water temperatures can range from 30 °F (−1 °C) to as high as 41 °F (5 °C) and salinities are in the low thirties parts per thousand. Unlike the Beaufort Sea, the waters in Baffin Bay circulate counterclockwise. The West Greenland Current transports the warm Atlantic water along the eastern boundary of the Bay (Fig. 2-4). By the time this current reaches the northern extremes of the Bay it has cooled but is still warmer and more saline than the Arctic water it meets there. At this northernmost point it converges with the Canadian Current. The resultant mixing significantly affects weather and sea conditions. Here the Canadian Current begins to transport water southward along the east coast of Baffin Island. This Canadian Current carries southward much sea ice and icebergs. South of the Davis Strait the Canadian Current is joined by the warmer waters of an extension of the East Greenland Current to form the Labrador Current.

These currents are responsible for the contrast of ice conditions between the eastern and western sides of Davis Strait. The warm West Greenland Current keeps the eastern part of the Strait virtually ice free the year round as far north as 70 °N. Conversely, the cold south-flowing Canadian Current keeps the western portion of the Strait filled with

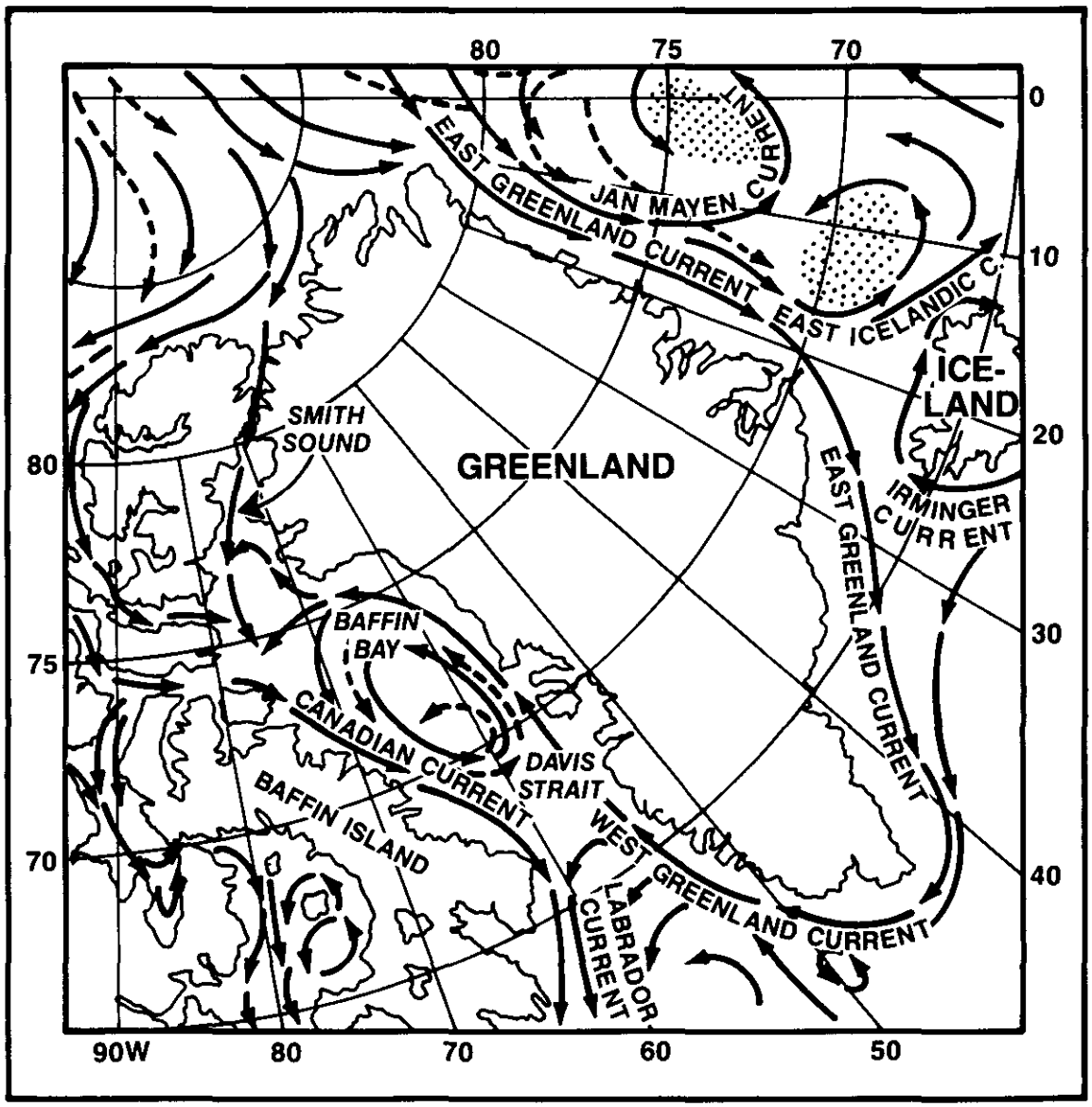

Figure 2-4. Greenland and Davis Strait Ocean Currents (adapted from Welsh et al., 1986).

ice throughout the year. The prevailing northerly winds in the area help to maintain a large patch of open water in Smith Sound (northern Baffin Bay), commonly referred to as *North water.*

The climate of the Baffin Bay area is sub-Arctic in the south and polar in the north, with coldest temperatures in the north and along the coast of Canada. High winds are common along the Greenland coast often due to katabatic (a wind blowing down an incline) flow off the icecap. These winds can rise quickly and often reach 65 kt (32 m/s). Fog is responsible for visibilities below 1.2 mi (2 km) 80 days/year. Winter temperatures range between −63 °F and 10 °F (−53 °C and −12 °C); in summer the range is between 10 °F and 50 °F (−12 °C and 10 °C). The lowest recorded temperature was −76 °F (−60 °C). Typical winds are northwesterly in winter and easterly in summer.

2.2.3 Greenland Sea

The large Greenland Basin reaches a maximum depth of 15,900 ft (4,846 m); the mean depth is 4,738 ft (1,444 m). The two basins of this sea contain deep water with a temperature of 30 °F (−1 °C) and salinity of 34.92 ppt. The Atlantic water above the deep water comes from the Irminger Current and is warm (>46 °F (8 °C) and saline (>35 ppt). To the south, vertical mixing of Atlantic water and Arctic water in winter results in a homogeneous water mass in the upper layers. This water is warmer, less saline, and called North Icelandic winter water.

The principal current in the Greenland Sea is the East Greenland Current (Fig. 2-5). Locally, this current can reach speeds of 0.5 to 1.0 kt (25–50 cm/sec) just south of the Denmark Strait. A cyclonic gyre is located north of Jan Mayen between the Greenland Current and a branch of the Norwegian Current flowing west of Svalbard. This Greenland Gyre dominates the Greenland Basin.

Sea ice occupies the entire sea but is minimal in September. The Greenland Sea normally contains a large amount of old ice that comes from the Arctic Ocean. Icebergs from the east coast of Greenland are also common.

The climate of the Greenland Sea area is polar. Visibility is less than 1.25 mi (2 km) for about 20 days/year in the north and 30 days/year in the south. Summer is the foggiest season. In the north, the record low temperature is −60 °F (−51 °C); in the south −29 °F (−34 °C). Winds can exceed 21 kt (11 m/s) 26 days/year in the north and 74 days/year in the south. Correspondingly, the sea state is much greater in the south.

2.2.4 Norwegian Sea

The Norwegian Sea is made up of North Atlantic water and Norwegian Deep water. The latter is formed in winter near Jan Mayen Island in the western part of the sea. The North Atlantic Current provides the warm, saline Atlantic water to the Norwegian Sea and helps to keep it ice free throughout the year.

The Norwegian Gyre is cyclonic and in the center of this sea. It moves water southeastward north of Iceland. The climate of the Norwegian Sea area is sub-Arctic. Precipitation is rather extensive here because the sea lies in the midst of major storm tracks. This fact also explains the generally rough seas. Visibility is less than 1.25 mi (2 km) for about 160 days/year due to low cloudiness and fog.

Winter temperatures range from 30 °F to 39 °F (−1 °C to 4 °C); in summer the range is 30 °F to 50 °F (−1 °C to 10 °C). The lowest recorded temperature is 10 °F (−12 °C), which is considerably warmer than the other sea areas examined so far.

2.2.5 Barents Sea

Barents Sea lies entirely over the continental shelf and therefore is quite shallow. Its mean depth is only 750 ft (230 m). Small tongues of Atlantic water enter the Barents Sea from the Arctic Basin at depths of 490 to 655 ft (150–200 m) through the deep straits between the islands.

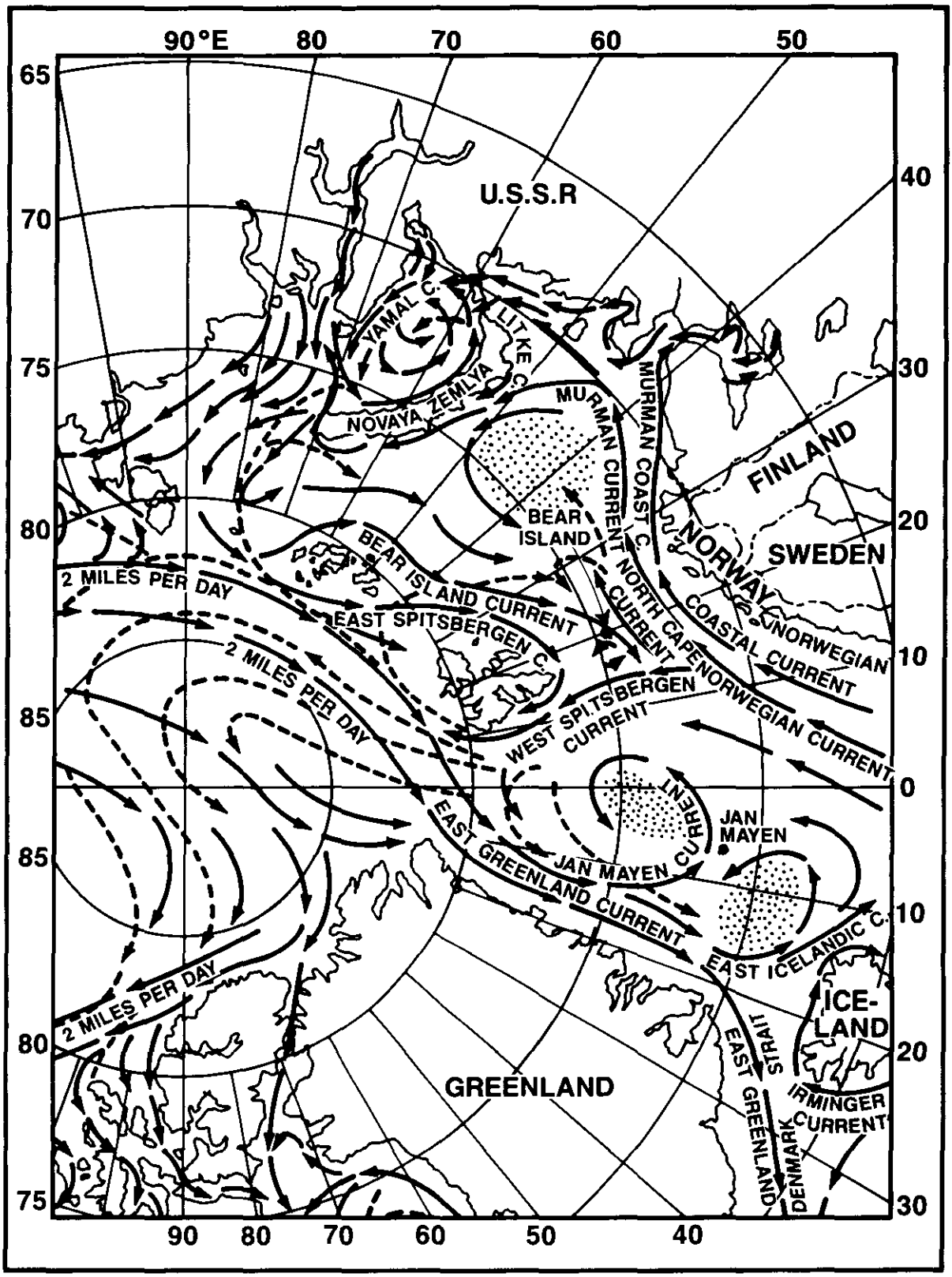

Figure 2-5. East Greenland to U.S.S.R. Ocean Currents (adapted from Welsh et al., 1986).

The circulation of the Barents Seas is counterclockwise with the Norwegian Coastal Current and Norwegian Atlantic Current merging to form the warm and saline North Cape Current. Bear Island is the site of the mixing of several currents. The cold Arctic water in the Bear Island Current mixes with the warm, saline Atlantic water and establishes a frontal zone in the vicinity of the island.

Sea ice is rare in the southwestern portion of the Barents Sea. In April, however, the sea can be 75 percent ice covered. Ice buildup is least in September and in some years, during September, the entire sea has been ice free. The large expanses of open water in the Barents Sea make the ice susceptible to wide variations in location.

The Barents Sea, being on the storm track, has wide weather variations and is a highly unstable region of the Arctic. Coupled with the open nature of the sea ice, the active wind regimes associated with the storms make for rough seas and high waves. Visibility is restricted to less than 1.25 mi (2 km) about 90 days each year. The winter temperatures range between −26 °F to 5 °F (−32 °C to −15 °C); in summer the range is from 32 °F to 45 °F (0 °C to 7 °C). The record low temperature is −60 °F (−51 °C), and the temperature may be less than −25 °F (−31.5 °C) 70 days/year. Winds may exceed 21 kt (11 m/s) 34 days/year. Half the year, seas may exceed 5 ft (1.5 m).

2.2.6 Kara Sea

Like the Barents Sea, the shallow Kara Sea lies entirely on the continental shelf, has a mean depth of 387 ft (118 m) and a maximum depth of 2,035 ft (620 m). Due to the fresh water supplied by the Ob and Yenisei Rivers, the salinity of the surface water is low, from about 7 to 20 ppt. This fresh water supply sets up a northward-moving current along the coast of Taimyr. In the southwest of the sea this current sets up a counterclockwise eddy.

Ice conditions are highly variable in the Kara Sea, but ice is apt to be heavy either in the northwest or in the southwest. Small icebergs are found north of Novaya Zemlya and Severnaya Zemlya (Fig. 2-6). Here the ice may be 5- to 10-ft (1.5- to 3-m) thick in winter, and large hummocks appear to heights of 30 ft (9 m). These "stamukhi" tend to be grounded, which limits movement of the ice pack (see Ice Glossary, Appendix A). East winds drive much ice between the islands, making the straits there impassable.

The climate of the Kara Sea is polar. Precipitation is less than 4 in (10 cm) per year. Visibilities are generally poor, less than 1.25 mi (2 km) about 130 days/year.

Wintertime temperature ranges from −20 °F to 25 °F (−29 °C to −4 °C); in summer it is more like 10 °F to 45 °F (−12 °C to 7 °C). The lowest recorded temperature is −54 °F (−48 °C), and the temperature can be below −25 °F (−31.5 °C) 30 days/year. Winds tend to be southerly in winter, northerly in summer. These winds exceed 21 kt (11 m/s) 70 days/year. The light winds and extensive pack ice allow seas in excess of 3 ft (1 m) only rarely.

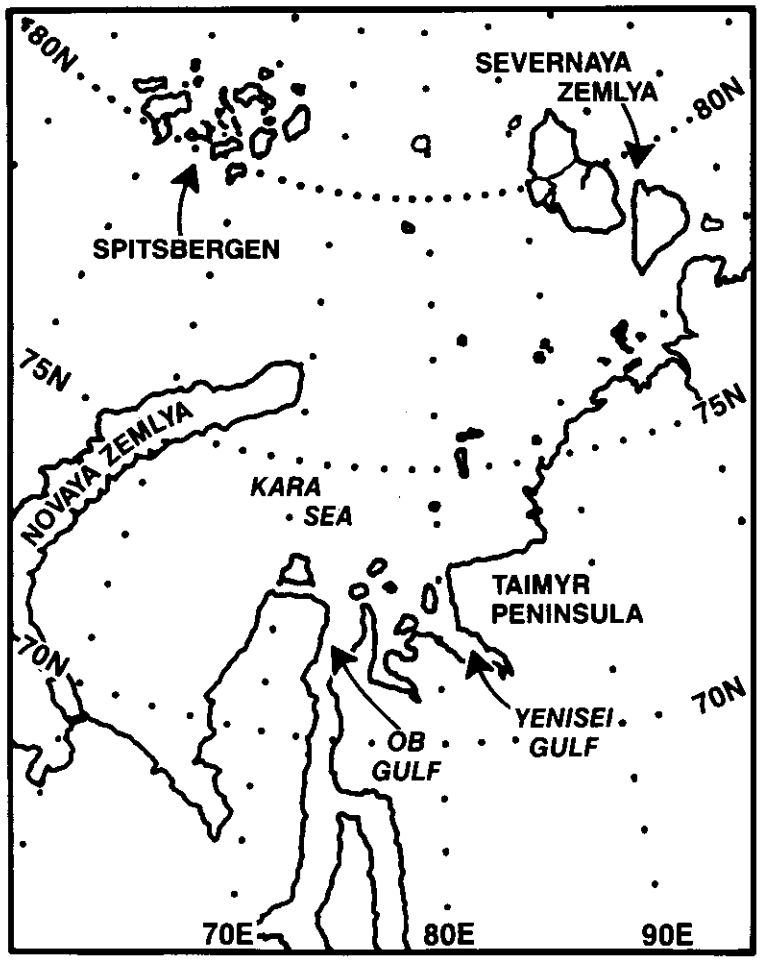

Figure 2-6. Kara Sea Region.

2.2.7 Laptev Sea

Sixty-four percent of the Laptev Sea is less than 328 ft (100 m) deep. Characteristics of the Laptev Sea are, therefore, highly dependent on seasonal ice cover and storminess. The surface water has relatively low salinities and varies, as does the temperature, with distance from the coast. Near the coast temperatures are up and salinities down.

The circulation in the Laptev Sea is counterclockwise, splitting at the Lena Delta (Fig. 2-7). One part moves north to the Arctic Drift, and the other part flows into the East Siberian Sea, east of the New Siberian Islands.

The climate of the Laptev Sea is definitely polar. The precipitation is light, and the year round sea ice precludes high seas. Visibility is less than 1.25 mi (2 km) for 75 days/year due to fog in the summer and blowing snow during the winter months. Winter temperature range is −29 °F to 1 °F (−34 °C to −17 °C); in summer, 10 °F to 45 °F (−12 °C to 7 °C). The record low temperature is −54 °F (−48 °C), and the temperature may be less than −25 °F (−31.5 °C) 60 days/year. Winds are highly variable from southeast to northwest, and winds can exceed 21 kt (11 m/s) 50 days/year.

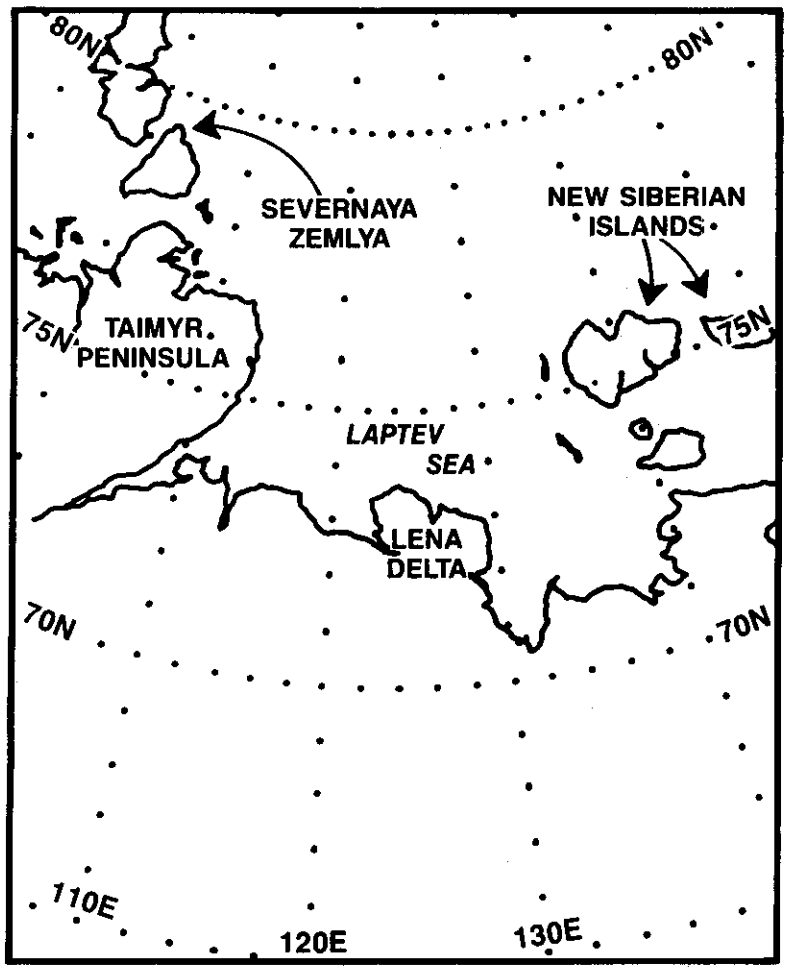

Figure 2-7. Laptev Sea Region.

2.2.8 East Siberian Sea

One of the shallowest of the Arctic seas, the East Siberian Sea depths range from 33 ft to 60 ft (10–20 m) in the western and central regions of the sea to 98 ft to 131 ft (30–40 m) in the east. Not unlike the Laptev Sea, the East Siberian Sea's water characteristics depend largely on ice conditions and river runoff. The eastern part of the sea is usually colder and more saline. Even so, salinities can be as low as 10–15 ppt and increase to 30 ppt near the edge of the ice. At the ice edge, temperatures are usually near 32 °F (0 °C) and increase to as much as 42 °F to 44 °F (6 °C to 7 °C) in late summer near the mouths of the rivers with a south wind blowing.

River outflows tend to give a counterclockwise circulation to the waters of the East Siberian Sea. The sea is characterized, however, by a very heavy ice cover and small icebergs from nearby islands. When the polar anticyclone weakens, thus widening the cyclonic water circulation, an increase occurs in pack ice from higher latitudes into the sea. The navigation season is 6 to 8 weeks in the east and 8 to 10 weeks in the west.

The East Siberian Sea has a polar climate. Winter temperatures range from −35 °F to 5 °F (−37 °C to −15 °C); in summer the range is 10 °F to 45 °F (−12 °C to 7 °C).

The record low temperature is −54 °F (−48 °C). Meanwhile, the winds are predominately east and northeast in summer and west to southwest in autumn. The northwesterlies can be quite strong, reaching 39 kt to 49 kt (20–25 m/s), and hence may generate 13 ft to 16 ft (4–5 m) waves. Winds can exceed 21 kt (11 m/s) 23 days/year. Visibility is restricted to less than 1.25 mi (2 km) for 90 days/year.

2.2.9 Chukchi Sea

The Chukchi Sea is that portion of the Arctic Ocean lying immediately north of the Bering Strait (Fig. 2-8). Its area is 225,000 sq mi (582,000 sq km). It is everywhere underlain by the continental shelf. Depths for the most part are between 35 and 213 ft (65 m). Two submarine canyons cross the shelf. Barrow Canyon extends northeast from about 80 mi (150 km) west of Point Barrow to terminate into the Beaufort Sea north of Point Barrow. Herald Canyon is situated northward along 175 °W, from 70 °N to the edge of the continental shelf.

The circulation in the Chukchi Sea is broadly cyclonic. Warm water enters through the eastern side of the Bering Strait throughout the year. In July and August the surface

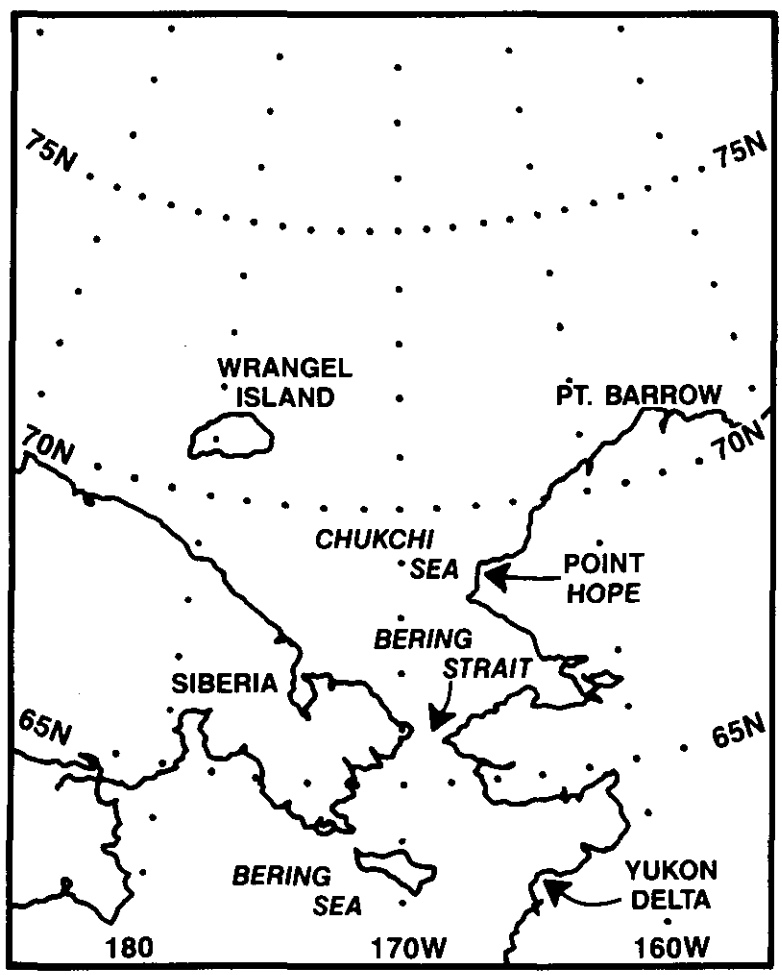

Figure 2-8. Chukchi Sea Region.

temperature of this stream may be 50 °F (10 °C), with salinity less than 30 ppt due to the runoff from the Yukon River south of the Bering Strait. The current divides near Point Hope. One portion continues northeastward toward Point Barrow where it turns westward and joins the general Arctic Basin circulation. The other portion branches northwestward from Point Hope to pass north of Wrangel Island. A cold current sets southeastward from the East Bering Sea along the Siberian coast toward the Bering Strait. It usually turns north before reaching the Strait, but exceptionally may flow southward through the Strait on its western side.

The cold flow of water along the Siberian coast toward the Bering Strait contrasts with the warmer, more saline water to the east. August surface temperatures in this flow range from about 32 °F (0 °C) at the western edge of the Chukchi Sea to 43 °F (6 °C) off Mys Dezhneva. Salinity is low, less than 29 ppt, and sometimes much lower, due to discharge from the Siberian rivers.

2.2.10 Sea of Okhotsk

The Sea of Okhotsk is located where the continent of Asia is separated from the Pacific Ocean by the Kuril Islands and the Kamchatka Peninsula (Fig. 2-9). Depths in the Sea

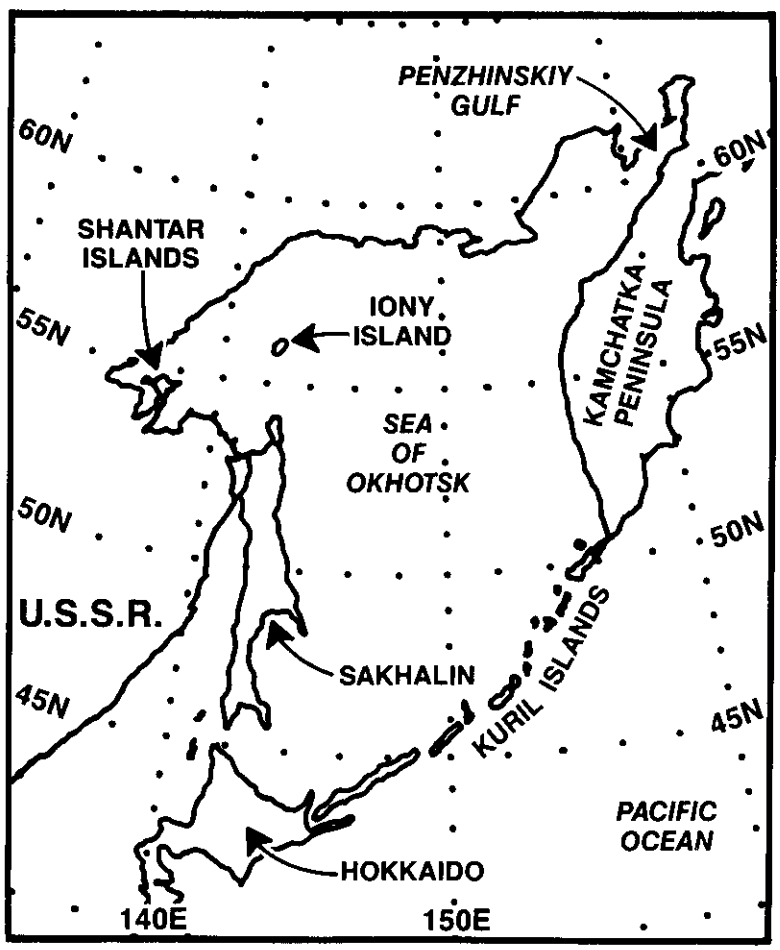

Figure 2-9. Sea of Okhotsk Region.

of Okhotsk range from a shelf under 600 ft (183 m) in the north to over 10,800 ft (3,292 m) near the Kuril arc, but here the slope between the two is gradual except off the east coast of Sakhalin, where it is fairly steep.

The general circulation in the Sea of Okhotsk is cyclonic and runs strongest 20 to 40 mi (30–60 km) offshore. A complex pattern of currents has been reported from the middle of the sea. The current moves north along western Kamchatka at 0.5 kt (25 cm/sec); in other sectors velocities up to 1 kt (50 cm/sec) are recorded. The Sea of Okhotsk has one unusual feature that affects both the ice conditions and the climate: the patches of substantially colder water (34 °F to 43 °F or 1 °C to 6 °C) that are located at the entrance of Penzhinskiy Gulf in the northeast, off Iony Island, and between the Shantar Islands and northern Sakhalin. These cold spots mark upwellings of colder, deeper water, the cause of which is still in doubt. They are associated with continuous dense fogs in the summer and concentrations of ice in the winter. The exchange of water with the Pacific Ocean is not great, due to the shallow depths (1,558 ft or 475 m) of the channels between the Kuril Islands. Pacific waters normally enter through the northeastern channels and Okhotsk water leaves by the southwestern channels.

2.3 Major Islands and Other Land Forms

2.3.1 Alaska and the Aleutian Islands

A primary characteristic of this region of the Arctic is the mountainous terrain. The Aleutians extend for more than a thousand miles from the Alaskan Peninsula to Attu Island (Fig. 2-10). Unimak is the easternmost island, and it is the largest of the 150 islands—about 65 mi (106 km) long and 25 mi (40 km) wide. The islands are, in some instances, glaciated and volcanic. Though treeless they support fairly luxurious growths of grass and willow and alder shrubs. They are noted for periods of extensive fog and sometimes gusty winds, called williwaws. The island area is known best as the birthplace of the Aleutian Low. The islands experience highly variable weather due to the frequent cyclonic storms in the area. Sea currents are swift around the islands and fog is frequent. On Unalaska Island, Dutch Harbor has a mean temperature of 32 °F (0 °C) in January and 51 °F (10.5 °C) in July, which is representative of most of the towns. Precipitation varies between 50 to 70 in (127–178 cm) annually.

The mainland of Alaska is meteorologically significant because of the Brooks Range, a range of mountains extending west to east in the northern quarter of Alaska. The area from these peaks to the north Alaskan coast is known as the *North Slope.* In subsequent chapters, the role of all these features that affect Arctic weather will be explored.

2.3.2 Canadian Arctic Archipelago

The many islands of the archipelago form a triangle with apexes at 61 °N in the east, 67 °N in the west, and the northern tip of Ellesmere Island at 83° 30′N (Fig. 2-11). Islands lying north of 74 °N are called the Queen Elizabeth Islands. Most of these islands are glaciated and mountainous, with remnant icecaps on Ellesmere, Axel Heiberg, Devon, and Bylot Islands.

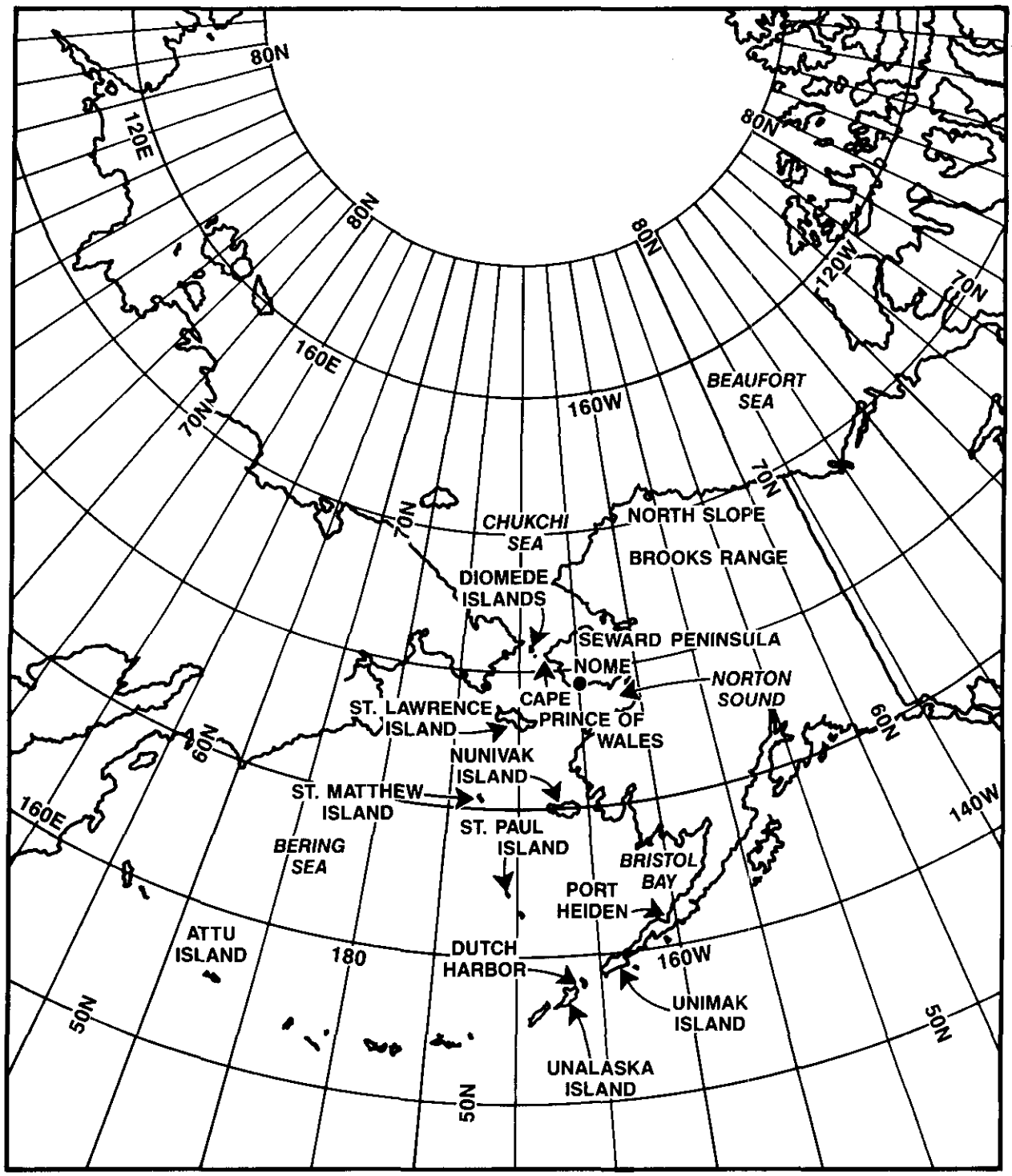

Figure 2-10. Alaska and the Aleutian Islands.

Figure 2-11. Canadian Archipelago Region.

The climate here is sub-Arctic in the south and polar in the north, as winters are long and cold with mean temperatures between −30 °F to −20 °F (−35 °C to −29 °C). February is the coldest month with temperatures dropping usually to between −35 °F and −40 °F (−37 °C and −40 °C). The record low temperature is −63 °F (−53 °C). The warmest areas are those exposed to the open waters of the Davis Strait in summer. July mean temperatures range between 40 °F and 50 °F (4.5 °C and 0 °C), with most stations reaching 60 °F (15.5 °C) sometime during the summer.

Precipitation is relatively light over the entire archipelago and rarely does it exceed 10 in (25 cm) annually. About half of the precipitation falls in the form of snow, which is likely in any month of the year.

2.3.3 Ellesmere Island

Ellesmere Island is the third largest and most northern island in the Canadian Archipelago. It is part of Canada's Northwest Territories (NWT). Weather stations were established on the island's southwest side at Eureka in 1947 and at Alert in the northeast in 1950.

Ellesmere Island is mountainous and has several icecaps. Numerous fjords indent the entire coast, but the most impressive one is the 200 mi (320 km) long Nansen Sound-Greely Fjord on the west coast. Northeast of this fjord are the plateau and lowlands. A rather unique ice shelf is found along the north coast, and the south and east coasts have open water only briefly in late summer.

The climate is cool and damp with temperatures rarely rising above 40 °F (4 °C). Short spells of warm weather can occur in the interior, however, where temperatures may reach 60 °F to 70 °F (15 °C to 20 °C).

2.3.4 Baffin Island

Baffin Island is about 1,000 mi (1,600 km) long and up to 500 mi (800 km) wide. The area of this fifth largest island in the world, which lies in the Canadian Archipelago, is 183,810 sq mi (476,068 sq km).

The island is mountainous in the east where some glaciers and icecaps reach elevations in excess of 8,000 ft (2,400 m). Cumberland Sound and Frobisher Bay are the better known of the many bays and fjords fringing the Baffin Island coast. The west-central coast is lowland and the northern and southern areas are generally plateaus. Airports are located at Frobisher and Cape Dyer. Other landing strips are situated at Nanisivik, Pond Inlet, Clyde River and Broughton Island.

2.3.5 Greenland

The world's largest island, Greenland, is covered by a sheet of ice spread over 80 percent of its area of 700,000 sq mi (1,820,000 sq km). This ice sheet is the source of most of the North Atlantic's icebergs. In profile, the ice sheet forms three broad domes, the highest of which is more than 10,000 ft (3,048 m). The ice thickness alone is probably in excess of 7,000 ft (2,134 m). Tongues of ice extend from this huge sheet to the coast. Greenland's

northern tip at Cape Morris Jessup (83° 39′N) (Fig. 2-12) is the farthest northland of the Northern Hemisphere. It is 1,600 mi (2,575 km) from here to the southernmost point at Cape Farewell (59° 46′N). The width at the widest point is just under 700 mi (1,126 km). The ice sheet is absent in three main areas: in the southwest, where the inland ice is separated by 100 mi (161 km) from Davis Strait; north of Scoresby Sound in the east; and in Peary Land in the north.

Temperatures on the icecap range from −49 °F to 27 °F (−45 °C to −3 °C) throughout the year. The great elevation of the ice gives rise to spectacular katabatic winds all along the Greenland coast. This subject will be discussed further in subsequent sections. On the west coast, mean temperatures range rather uniformly from 18 °F (−8 °C) in February at Ivigtut in the southwest, to −20 °F (−28 °C) at Smith Sound in the northwest. Summertime temperatures are more uniform, 50 °F (10 °C) in the south and 35 °F to 40 °F (1 °C to 5 °C) in the north.

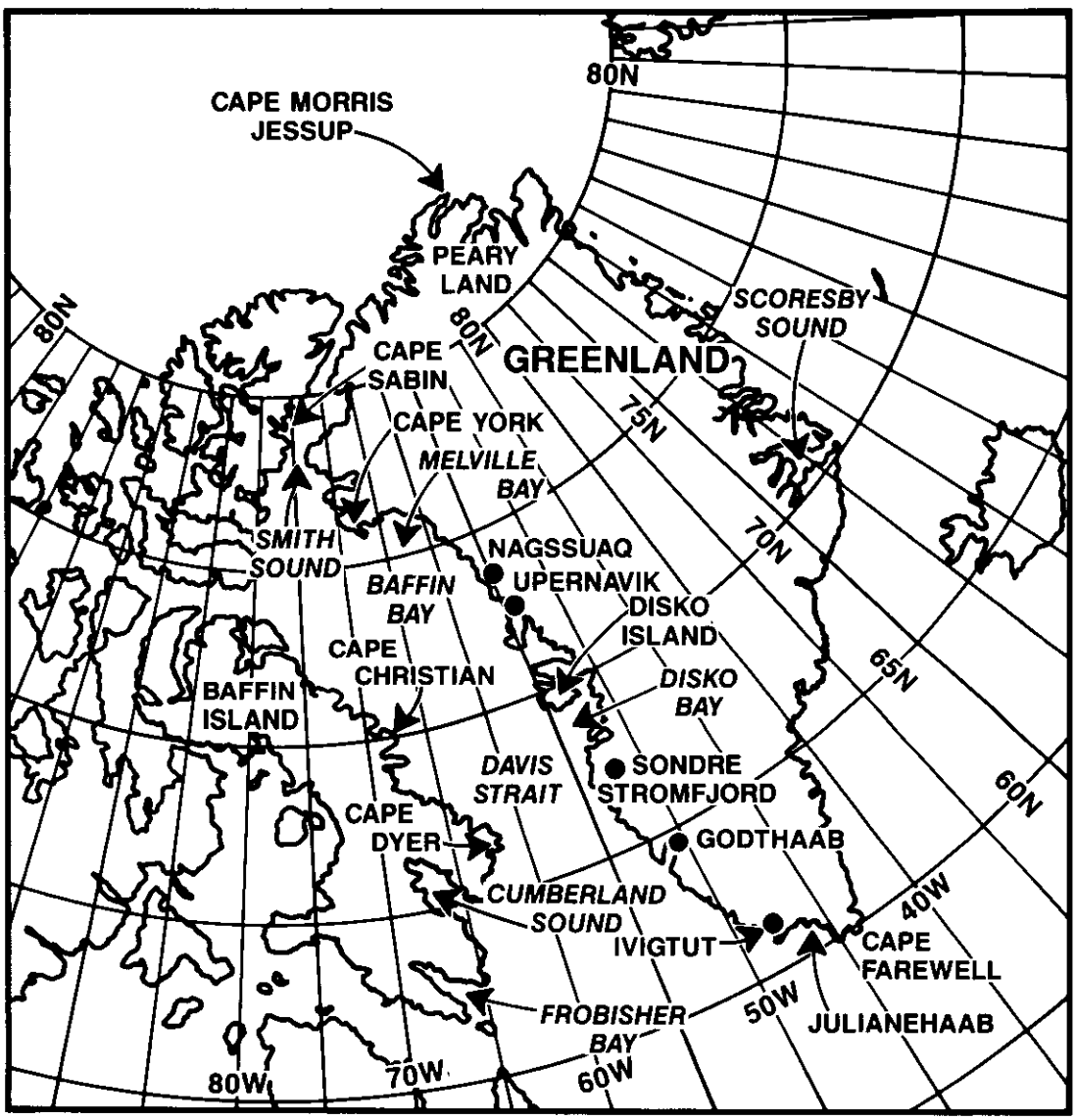

Figure 2-12. Baffin Island and Greenland.

Precipitation varies from 46 in (117 cm) of snow at Ivigtut in the south to 10 in (25 cm) north of 69 °N. Except for portions of the southeast coast, the entire island is ice locked in winter and fog is prevalent, especially near the broken ice. Fog or stratus will form over the marginal ice zone with on-ice wind flow.

2.3.6 Svalbard (Spitsbergen)

Svalbard is an Arctic archipelago made up of a main group of large islands known as Spitsbergen, Bear Island, Hope Island, and some smaller islands (Fig. 2-13). The Spitsbergen Archipelago consists of West Spitsbergen, Prince Charles Foreland, Northeast Land, Barents Island, and Edge Island and has a total area of 23,700 sq mi (62,370 sq km). The entire Svalbard landmass is only slightly larger at 24,000 sq mi (63,158 sq km), and it contains several volcanic cones and hot springs.

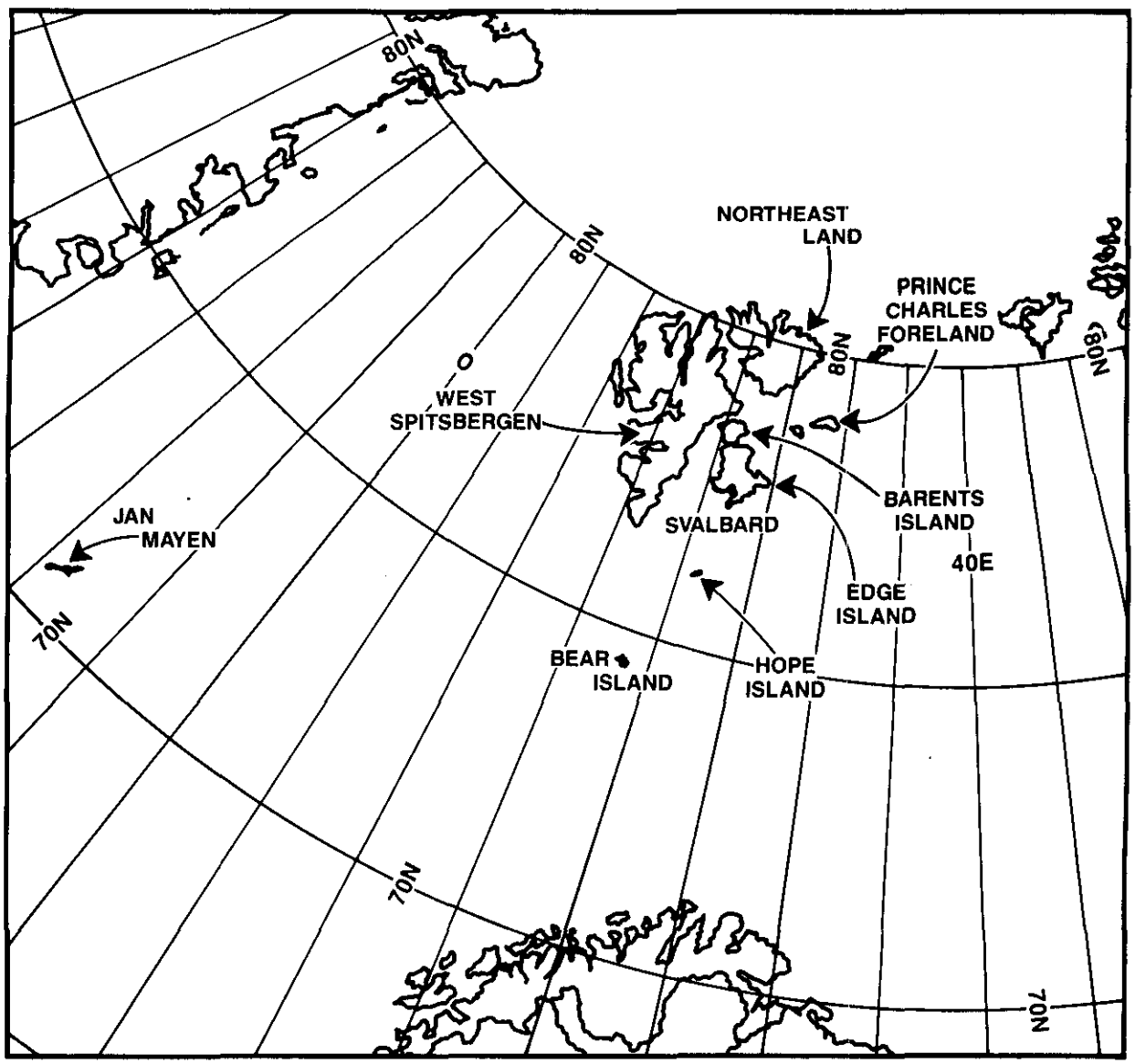

Figure 2-13. Svalbard Archipelago.

The Arctic climate here is stormy and rather mild in the west but much colder and quieter in the east. The islands are extensively glaciated (90 percent) but some peaks do penetrate the snowfields in the west and many of the valleys here are ice free.

2.3.7 Novaya Zemlya

Novaya Zemlya is also an archipelago consisting of two main islands and a number of smaller ones situated off the coast of European U.S.S.R. (Fig. 2-14). The total area of these islands is about 31,382 sq mi (81,593 sq km). The two main islands form a crescent shape and are separated by the Strait of Matochkin Shar. The Karskiye Vorota separates the archipelago from Vaigach Island to the southeast.

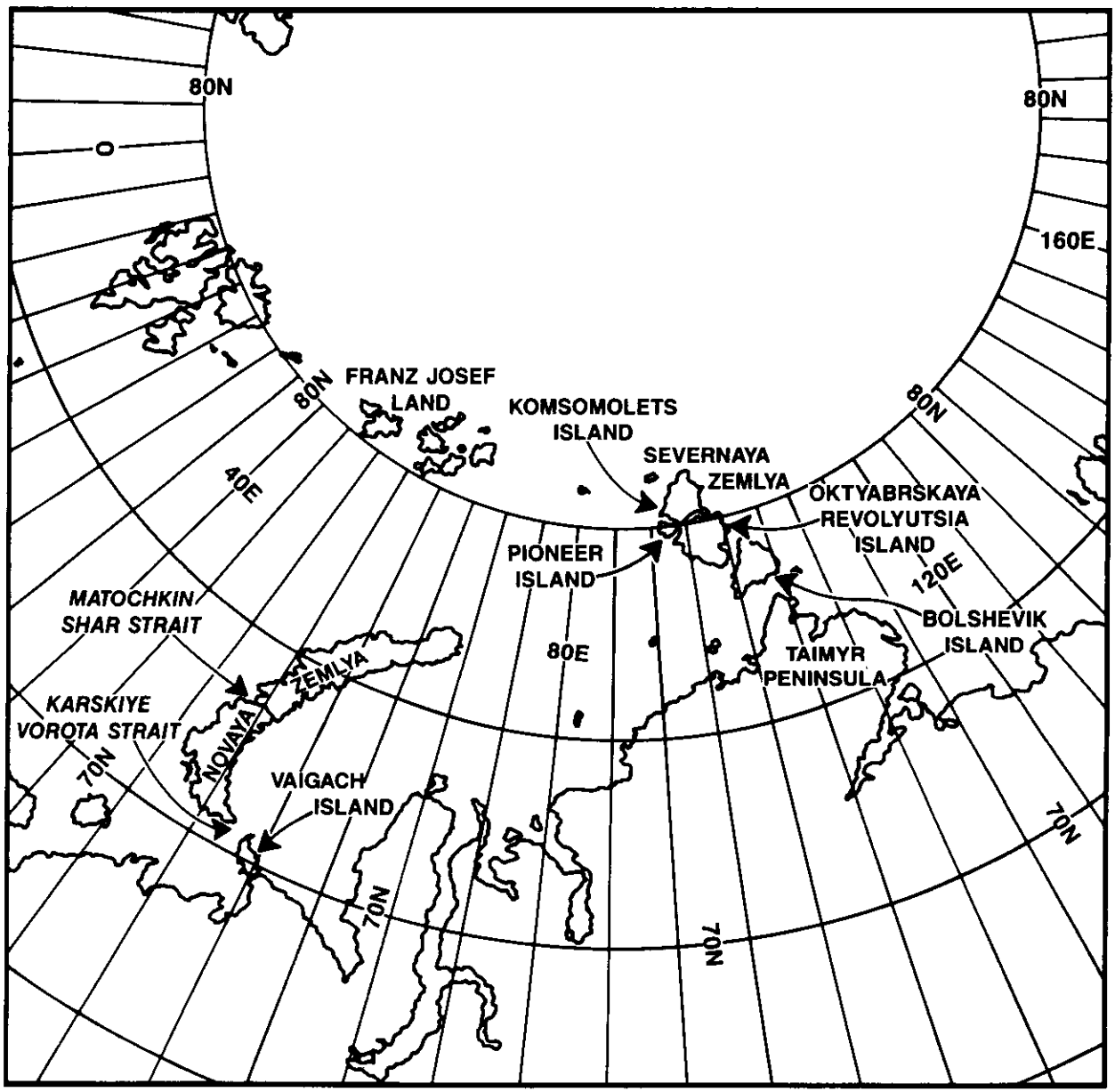

Figure 2-14. Novaya Zemlya, Severnaya Zemlya, and Franz Josef Land.

Novaya Zemlya is mountainous, being an extension of the Urals. The highest peak is on the southern portion of the island and reaches an elevation of 5,217 ft (1,590 m). The main northern island, having high terrain, is largely ice covered along a glacial ridge while the southern half is ice free, like an Arctic desert.

Average temperatures range from −7.6 °F (−22 °C) in January to 43.5 °F (6 °C) in July. Precipitation varies from 6 to 9 in (15–23 cm) annually.

2.3.8 Severnaya Zemlya

This island is an archipelago of the U.S.S.R. in the Arctic Ocean. Its name means "northern land." Separating the Kara and Laptev Seas, it lies north of the Taimyr Peninsula (see Fig. 2-5) and is part of the Russian Republic. Slightly less than half of its area of 14,300 sq mi (37,000 sq km) is ice covered. The four main islands are Komsomolets, Pioneer, Oktyabrskaya Revolyutsia, and Bolshevik.

2.3.9 Franz Joseph Land

This Arctic archipelago belongs to the U.S.S.R. and lies east of Svalbard and north of Novaya Zemlya (Fig. 2-14). It is made up of about 100 islands that lie between 80 °N and 82 °N, and 43 °E and 65 °E. The islands are similar in appearance and have glaciers and icecaps over the thousand-foot-high landmasses. Perhaps as much as 90 percent of their area is covered by ice; the smaller islands are completely buried in ice.

2.3.10 Jan Mayen

Jan Mayen is a bleak and desolate Arctic island between Greenland and northern Norway at about 71 °N 8 °W (Figs. 2-13 and 2-15). It is 33 mi (53 km) long and 10 mi (16 km) wide at its greatest breadth. Jan Mayen is of volcanic origin and has two major peaks: Beerenberg (7,470 ft or 2,277 m) in the northeast and Rudolftoppen (2,525 ft or 769 m) 25 mi (40 km) away to the southwest. The two peaks are joined by a ridge that is at all points at least 656 ft (200 m) in elevation.

Glaciers on the islands are fully developed, and the climate is cold and foggy. It is named for a Dutch whaler captain named Jan Jacobsz May. Its Norwegian weather station has been in operation since 1921. It is home to a NATO airport.

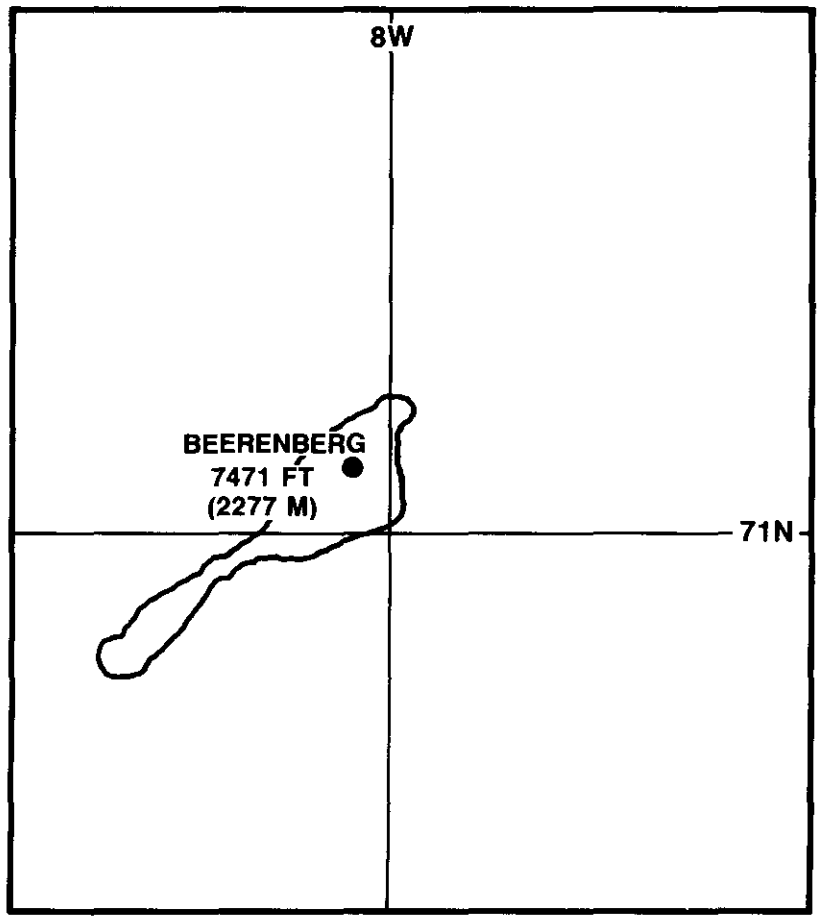

Figure 2-15. Jan Mayen.

2.4 The Arctic Ice

2.4.1 Ice Coverage Characteristics

The ice that covers the Arctic Ocean is constantly on the move in response to wind and ocean currents. Its response to the seasons is dramatic: the average area of ice coverage can shrink from 4.7 million sq mi (11.7 million sq km) in late winter to half that size in late summer. Figure 2-16 shows the average annual maximum and minimum ice limits in the Arctic and sub-Arctic regions. The area between these two limits is known as the *Marginal Sea Ice Zone.* (Hence, the acronym *MIZEX* for the marginal ice zone experiments conducted in the 1980s.)

In some areas near the edges of the ice sheet, waves and swells can also affect the ice motion. Variable stresses such as tensile, shear, and compressive are constantly at work to cause ice floes to separate and produce open water lanes (LEADS) or open water "lakes" (POLYNYI). In contrast, floe collisions may cause the ice to pile up in huge HUMMOCKS or RIDGES that may reach 33 ft (10 m) in height above water and 164 ft (50 m) below. When occurring near shorefast ice, the collisions create chaotic zones of rubble, hummocks, and pressure ridges that collectively become known as a FLAW.

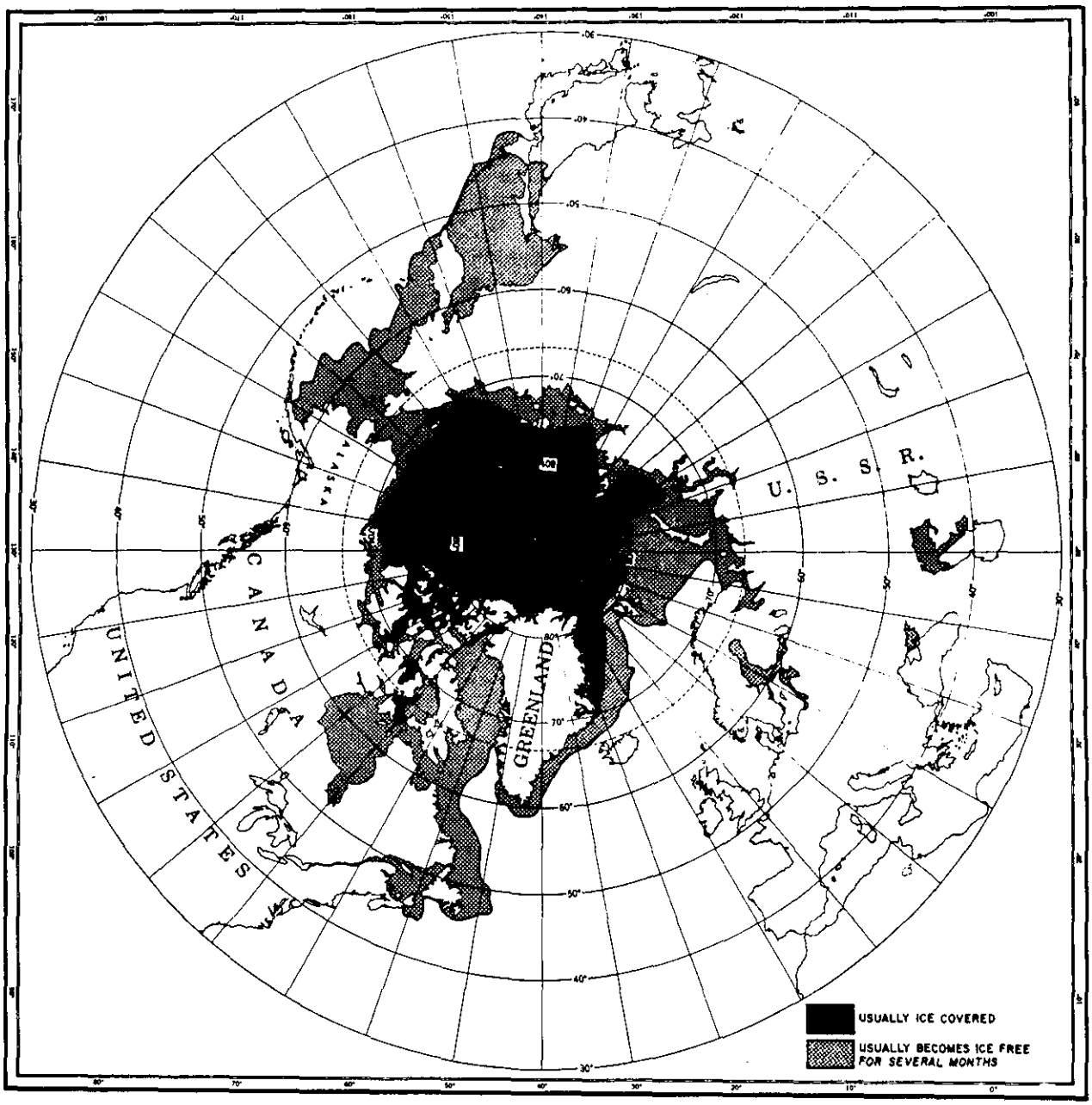

Figure 2-16. Average Annual Maximum and Minimum Ice Coverage (Sater et al., 1971).

2.4.2 Development of Sea Ice (Adapted from Lopez, 1986.)

SEA ICE forms differently from lake ice. Because the maximum density of lake water occurs at 39 °F (4 °C), it expands on falling below that temperature, has less density, and therefore rises. Hence, the bulk of the lake remains at 39 °F as ice formation takes place on the surface. After that, additional ice forms on the bottom of the ice surface.

Sea ice does not achieve its maximum density, or start freezing, until it is cooled to 28.6 °F (−2 °C). In its initial stages, the crystalline structure of sea ice incorporates brine and is not solid. It will, therefore, bend under a load before it fractures, while newly formed freshwater ice, brittle and also more transparent, will fracture suddenly, like a windowpane. Because of its elasticity, even sea ice 4 in (10 cm) thick is unsafe to walk on, while freshwater ice only half as thick will support a human being.

"In the absence of any wind or strong current, sea ice first appears on the surface as an oily film of crystals. This FRAZIL ICE thickens to a kind of gray slush called GREASE ICE, which then thickens vertically to form an elastic layer of ice crystals an inch (2–3 cm) or so thick called NILAS. Young nilas bends like watered silk over a light ocean swell and is nearly transparent (i.e., dark like the water). When it is about 4 in (10 cm) thick, nilas begins to turn gray and is called YOUNG ICE, or GRAY ICE. When gray ice finally becomes opaque it is called FIRST-YEAR ICE. And in these later stages it thickens more slowly."

Although sea water has a salinity in the vicinity of 35 ppt, ice grown from sea water seldom has a salinity greater than one-third or one-fourth this value. Frazil ice crystals are nearly pure water. When a mass of frazil crystals congeal to form nilas, however, they entrap pockets of sea water between them, some of which have an elevated salt content caused by the expulsion of salts during the freezing of the frazil crystals. Ice older than one melt season has a much lower salinity than first-year ice. The reasons for this are not well known. Nevertheless, the result is that OLD ICE is remarkably "fresh", with salinities varying around 2 ppt.

"By spring, first-year ice might be 4 to 6 ft (1–2 m) thick. If it does not melt completely during the summer, it becomes SECOND-YEAR ICE in the fall, tinted blue and much harder. Brine in the upper layers has drained out during the summer and fresh ice crystals have filled the drained areas. Second-year ice continues to thicken, until it stabilizes after a few years at about 10 to 12 ft (3–4 m). If it remains unmelted through a second summer, it is simply called MULTIYEAR ICE, or polar PACK ICE, to distinguish it from first and second year pack ice."

The albedo of ice strongly depends on its age and thickness. Frazil or new ice up to 2 in (5 cm) thick has a very low albedo and actually appears dark against a water surface. LIGHT NILAS, measuring 2 to 4 inches (5–10 cm) in thickness, has a low albedo and appears dark gray. Young ice between 2 and 4 in has a moderate albedo and appears grayish. First-year ice with thickness greater than 12 in (30 cm) has a relatively high albedo of reflected *visible* light and appears very light gray against SNOW-COVERED ICE. Albedos in the infrared are different and will be discussed elsewhere.

2.4.3 Ice of Land Origin

Ice that has been formed on land as a result of the compaction of snow into GLACIERS is frequently found in certain regions of the Arctic. In these regions, the glaciers flow to the sea and form ice shelves. The ice shelves calve off ICEBERGS or ICE ISLANDS. Because of their large mass and unusual strength, icebergs are a hazard to navigation. Figure 2-17 provides size comparisons for ice of land origin. Ice that remains fixed to the coast is known as FAST ICE.

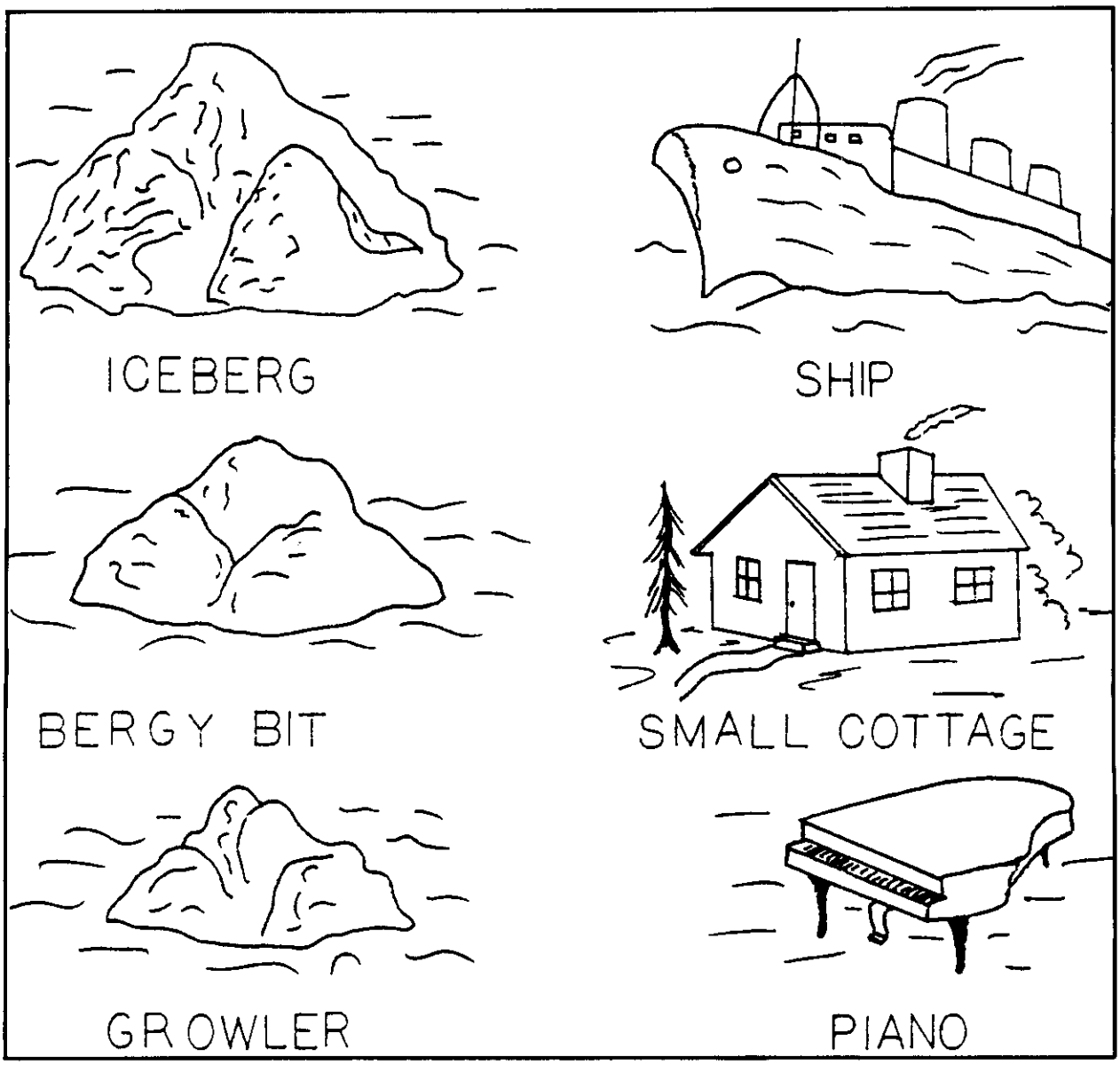

Figure 2-17. Comparison of Ice Sizes.

2.4.4 Ice Islands

Large sections of land ice (up to nearly 200 ft [60 m] thick and 20 mi [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 in the Beaufort (Pacific) Gyre. Eventually they disintegrate or exit into the Greenland Sea via the East Greenland Drift. Some have been recognizable for as long as 30 years. Almost as extensive as ice islands but much thicker are tabular icebergs, which break off whole from the foot of a tidewater glacier. With a volume of 40 to 50 cu mi (165–210 cu km), they are the largest objects afloat in the Northern Hemisphere.

2.4.5 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. The primary source of icebergs, however, is the Greenland ice sheet, which has a maximum thickness of 10,827 ft (3,300 m) and annually calves about 314,400 cu yds (240 cu km) 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 calved annually by the Greenland ice sheet vary from 20,000 to 34,000, with most being produced by the west coast of Greenland glaciers. Although these statistics are numerically impressive, they do not provide the volumetric or mass information needed to estimate 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 those icebergs calved from west coast glaciers. This drift continues northward 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.

2.5 Distribution of the Arctic Ice

In large part, the limits of the Arctic ice cover is determined by the bordering landmasses. The greatest variation in ice cover occurs in the marginal seas of the Chukchi and Bering Seas and Sea of Okhotsk on the Pacific side, and in the Greenland and Norwegian Seas and Baffin Bay on the Atlantic side.

The Arctic ice edge climatology charts for April (Fig. 2-18) and for October (Fig. 2-19) were constructed by graphically compositing the maximum and minimum ice edge extremes from eleven years (1972–82) of the Joint Ice Center's operational eastern and western Arctic ice analyses centered closest to the fifteenth of the month.

During the spring (March–April) the sea ice makes its deepest penetration southward. In the fall (September–October) the extent of the ice is at its minimum. Climate and ocean currents play the largest roles in determining the extent of the ice in any season. For example, the warm Atlantic Current continuously transports heat into the Norwegian Sea. Thus, the open water is indented poleward during all seasons in the eastern Atlantic sector. A comparison of fall and spring charts shows that the ice edge remains in the Svalbard region throughout the year. In the Barents Sea, where the effects of the Atlantic Current are less pronounced, the ice edge location is more variable.

As noted in the climatology charts, sea ice distribution can vary considerably from season to season and from area to area throughout the marginal Arctic seas. These changing conditions have a tremendous effect on the weather conditions in the Arctic, as well as the military's ability to operate in these areas. The successful Arctic forecaster must be knowledgeable about the changing sea ice conditions and their effects on Arctic operations. The following detailed descriptions of sea ice conditions in the Arctic Ocean and adjoining seas will assist in gaining that knowledge. The terminology used to describe these sea ice conditions is in accordance with the World Meteorological Organization's (WMO) Sea Ice Nomenclature, WMO-No. 259, TP 145, which is included as Appendix A.

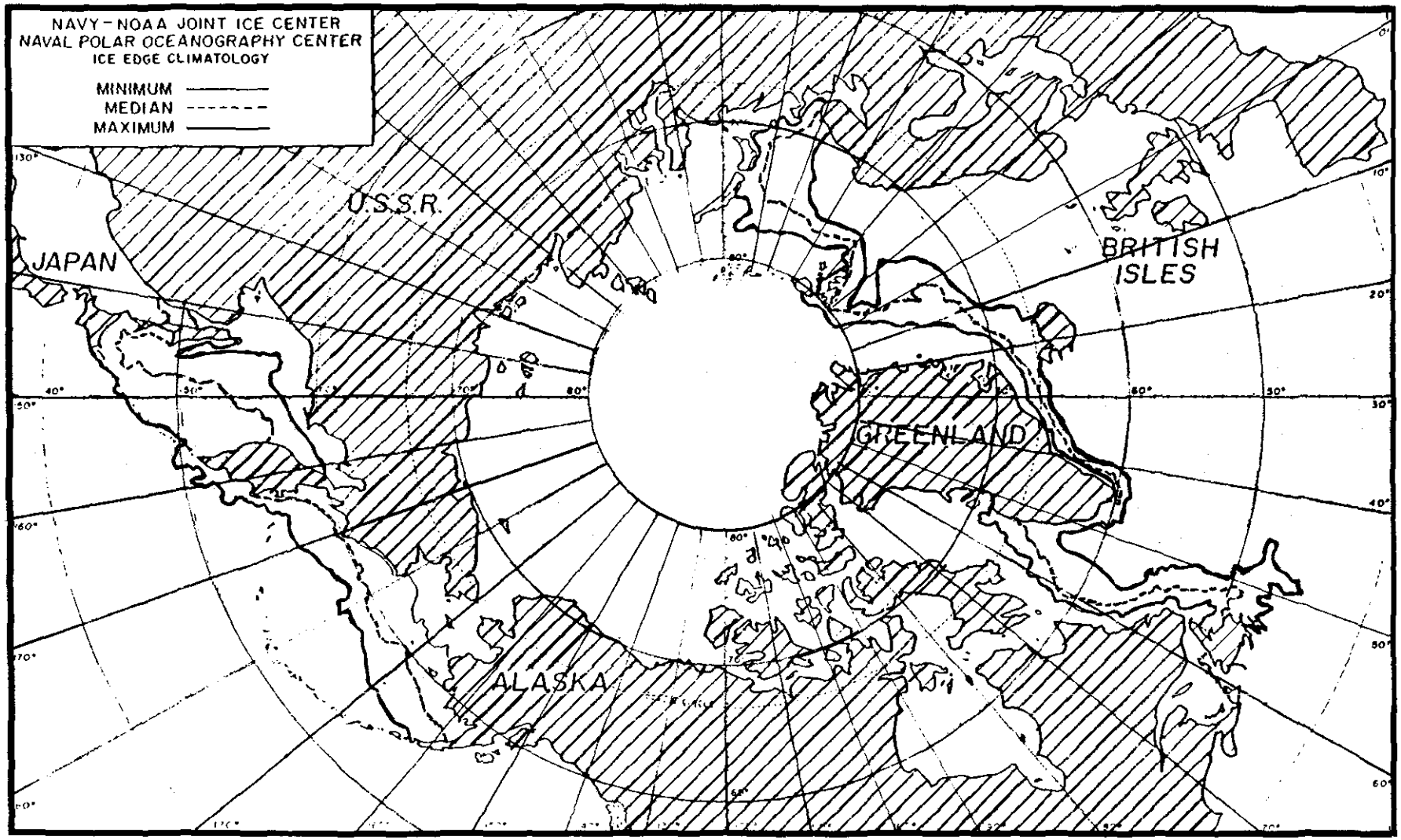

Figure 2-18. Statistical Ice Edges in the Northern Hemisphere (April) (Stringer et al., 1984).

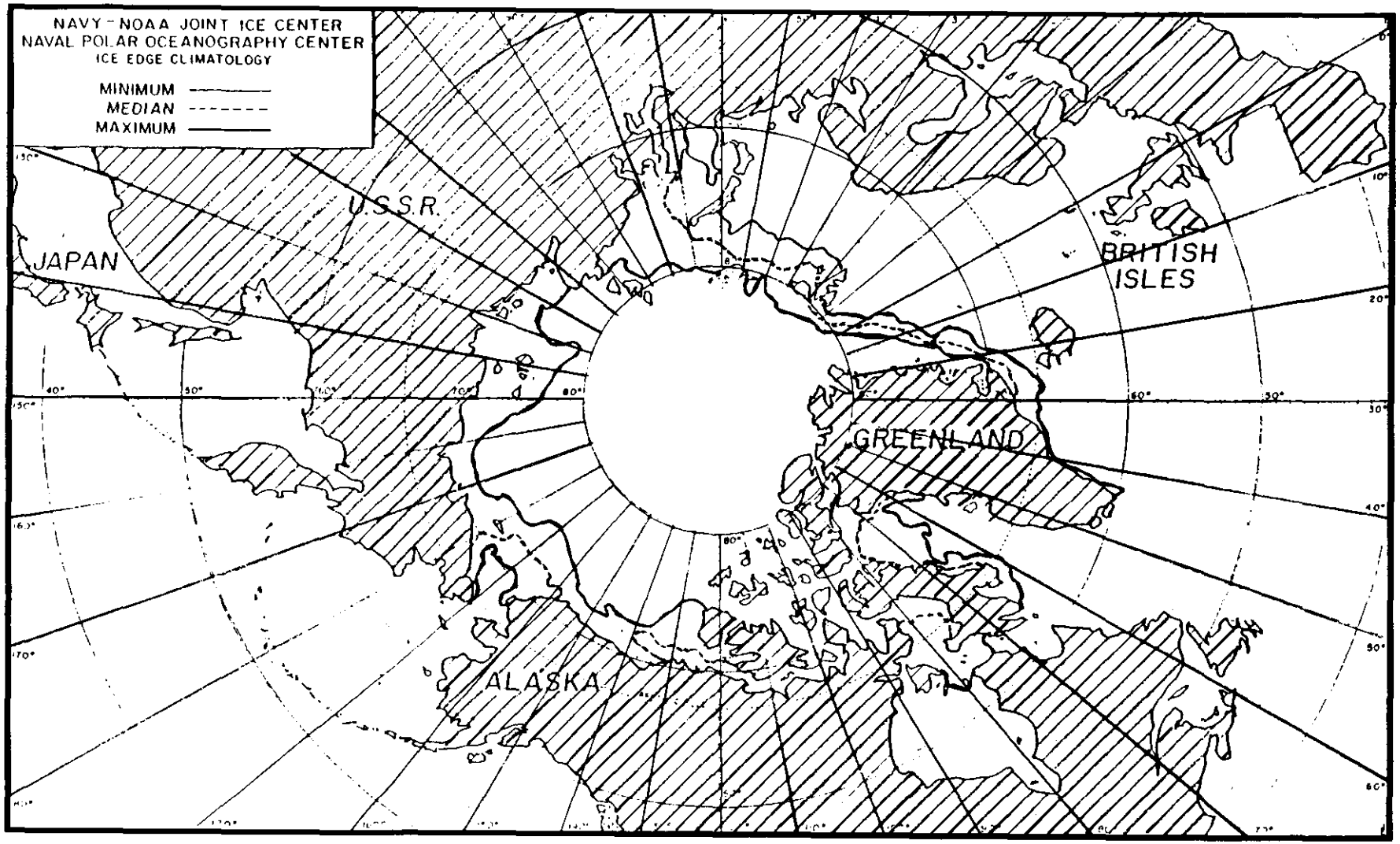

Figure 2-19. Statistical Ice Edges in the Northern Hemisphere (October) (Stringer et al., 1984).

2.5.1 General Ice Distribution in the Arctic Basin

The Arctic pack is a floating conglomeration of pieces of sea ice of all sizes, from huge masses many miles in diameter to small pieces not much larger than a normal office desk. In the winter, the whole Arctic Basin is covered by an elastic ice sheet in which many short narrow leads, cracks, and fractures are opened and closed by the stress of winds and currents and the effects of continual expansion and contraction of the ice itself. At any given time, even in the dead of winter, significant amounts of open water in the Arctic Basin can be found, but the water openings that do form are covered rapidly by new ice growth.

Within the Arctic Basin the freezeup starts in mid-September, and by mid-November the freezeup is complete throughout the Arctic Basin. Due to the prevailing northerly and northeasterly winds in the fall and winter months, the ice pack starts to close in on the shores of Alaska and the U.S.S.R. On the Alaskan coast the ice pack often moves onto the coast about mid-September but may retreat northward again off the coast. But by mid-October it is hard on the coast and stays throughout the winter. Islands off the coast of the U.S.S.R. (Novaya Zemlya, Severnaya Zemlya, and the New Siberian Islands) act as a barrier to the advancing polar ice pack and allow the areas to the south of the islands to remain ice free for a longer period of time than along the Alaskan coast. By mid-November, however, the U.S.S.R. coastal seas are covered by ice for the winter.

Ice breakup in the Arctic Basin does not occur as such. The summer melt starts in June and by mid-August is at its maximum. In midsummer as much as 5 percent of the Arctic Basin may become ice free as the first-year ice melts and the basin becomes dominated by multiyear and second-year ice. Vast amounts of puddling and many thaw holes become apparent as the first-year ice decays and eventually melts, leaving many cracks and leads throughout the Arctic Basin. Along the fringe or southern portion of the Arctic Basin are areas where the major ice melt and decay takes place and consequently, where ship navigation becomes possible. The summer melt of ice begins west of Point Barrow, Alaska with the northerly transport of warm water through the Bering Strait. At the same time, the land warms and relatively warm water begins to flow from the rivers. These warming waters act as melting agents that help open large shore leads along the coasts of Alaska and the U.S.S.R.

In midwinter the Arctic Basin is covered by some type of ice 99 percent of the time. As the wind and ocean currents move the ice pack, leads and cracks open in the pack and new ice forms rapidly in these openings. As the ice pack moves, the ice bangs and bumps together causing ridges of ice, called pressure ridges. Continual pressure on the ice from the prevailing north to northeasterly winter winds causes extremely large pressure ridges to develop for many miles along the coastal areas of Alaska and the U.S.S.R.

The currents of the Arctic Ocean form what is called the Arctic Gyre, which has a anticyclonic flow around the Arctic Basin. The Arctic Gyre slowly carries the ice pack in a anticyclonic whirl around the basin. So slowly, in fact, that it takes 15 to 20 years or longer for a piece of ice to complete this trip. As the ice rotates, some is expelled through the Bering Strait, Canadian Archipelago, and the East Greenland Sea. Ninety-five percent of the multiyear ice that is expelled from the Arctic Basin is through the East Greenland Sea. This ice slowly drifts southward, breaks up, and melts.

2.5.2 Ice Distribution in the Seas Bordering Alaska

Gulf of Alaska

Ice distribution in the Gulf of Alaska is limited to the formation of winter ice in the sheltered harbors and coastal indentations from mid-December to mid-April. The warm Alaska current keeps the area to the south of the Aleutian Island chain and the mainland free of ice in the unconfined areas.

Bering Sea

The Bering Sea is covered with vast expanses of winter ice. This ice is much thinner and weaker, however, than the ice formed in Baffin Bay and Davis Strait at equal latitudes. In fact, in the southern parts of the Bering Sea, the ice remains predominantly medium-winter thickness throughout the winter. Even the ice in the northern Bering Sea is seldom more than about 3 ft (1 m) thick. Several factors account for this characteristic: (1) the greater expanse and depth of the water, (2) the predominantly stronger winds, and (3) the warmer north setting currents.

The freezeup begins with fast ice formation along the Seward Peninsula (refer to Fig. 2-10) in early November. By the end of November, the pack ice normally extends south to about 60 °N, while fast ice can be found in the coastal indentations and bays as far south as Bristol Bay.

The maximum extent of the ice occurs in April. At this time the ice boundary normally extends from the coast at Port Heiden to St. Paul Island, and then to the west. South of about 60 °N the ice pack normally consists of BELTS and PATCHES drifting in random patterns. North of 60 °N a more or less continuous pack of heavy ice forms. The fast ice generally extends from 5 to 10 mi (10–20 km) offshore, being more extensive and heavier in Norton Sound and along the north coasts of Nunivak and St. Lawrence Islands. Areas of perennial open water (or at most thinner areas of young ice) exist in the vicinities of 63 °N 167 °W, 63 °N 174 °W, 64 °N 171 °W, and between Nunivak Island and the mainland.

The ice characteristics vary greatly north and south of 60 °N. To the north, the area is dominated by thick winter ice in the form of large, vast floes that are quite heavily ridged and virtually totally snow covered. South of 60 °N the ice is predominantly medium-winter thickness in small- to medium-sized FLOES, with rafting the predominant topographical feature.

Usually, extensive CRACKS and small leads will exist between the vicinities of Cape Prince of Wales and the Diomede Islands. The area where the Bering Sea meets the Chukchi Sea is one of conflicting currents. Most of the ocean currents in the Bering Sea set to the north. Due to these warm currents, and because total melt occurs annually in the Bering Sea, polar ice does not occur in this sea. Occasional pieces of ice will be seen that have the appearance of thick polar ice. These pieces, actually FLOEBERGS caused by the piling up of thin elastic and very weak ice caused by tidal and wind action, occur especially around the south coast of St. Matthew Island, the northeast coast of St. Lawrence Island, and the vicinity of the fast-ice edge at Nome.

The breakup process in the Bering Sea is quite rapid and is due almost entirely to warming temperatures and warm currents. The ice pack normally recedes to the north of St. Matthew Island by May, to the north of St. Lawrence Island by June, and to the north

of the Bering Strait by July. The fast ice along the coast usually disintegrates even more rapidly due to the more rapid warmup of adjacent land and the contribution of river runoff. This rapid disintegration results in the frequent appearance of leads along the coast as the breakup process begins.

Bristol Bay

Bristol Bay is open to shipping from early May to late November. During the winter, this area contains a narrow band of fast ice along the shore with belts and patches up to about seven-eighths concentration in the central bay. In the spring, disintegration occurs along the shore due to fresh water runoff, and along the seaward edge due to warming currents.

Norton Sound

Norton Sound is open to shipping from early June to mid-November. During the winter, the inner sound is covered with fast ice and the outer sound is covered by heavy winter ice formations. The latter is extremely difficult to penetrate due to heavy ridging. In the spring, the inner sound usually opens earlier than the outer sound.

Chukchi and Beaufort Sea

The ice conditions in both these seas are complex and are complicated by the erratic movement of the polar pack. The Beaufort Sea is affected more by this phenomenon than the Chukchi Sea.

In late October, the freezeup cycle begins. At this time the polar pack begins to move down the continental coasts under the influence of the predominantly seasonal northerly winds. At the same time, the bays and inlets along the coast begin to freeze over with fast ice. Throughout the year the Arctic pack is subject to moving against the coast. Toward the end of the shipping season in September, the shipping lanes are closed more and more frequently, and by late October or early November, the ice is on the coast to stay.

Winter ice in the Chukchi Sea is subject to considerable breakup due to the pressure of the wind, currents, and tides. Ice forms first in areas such as Kotzebue Sound in October (Fig. 2-20). By the first of November, the sound is completely covered except for scattered shore leads that open from time to time.

The breakup occurs in June, with scattered leads opening along the coastline from Cape Lisburne to Point Barrow. At about the same time, a lead commences to form at the mouth of the MacKenzie River. The leads gradually extend toward each other as the ice weakens and melts. Finally, the winter fast ice disintegrates and the Arctic pack recedes to the north. Usually, a lead can be navigated to Point Barrow by early July. By late July, the entire Alaskan coast is usually navigable, although it is subject to sudden closing due to shifts in the Arctic pack. The lead increases in width in August, the best month for navigation in this area. The lead varies in width from 3 to 5 n mi (5–10 km) to as much as 50 n mi (90 km) wide along the coast from Point Barrow to Barter Island. From Barter Island east to MacKenzie Bay, the lead widens considerably due to the influx of warm fresh water from the MacKenzie River. An area of year round open water normally exists in the Beaufort Sea, southwest of Banks Island, due to the abrasive action of the moving Arctic pack against the fast ice of the coast.

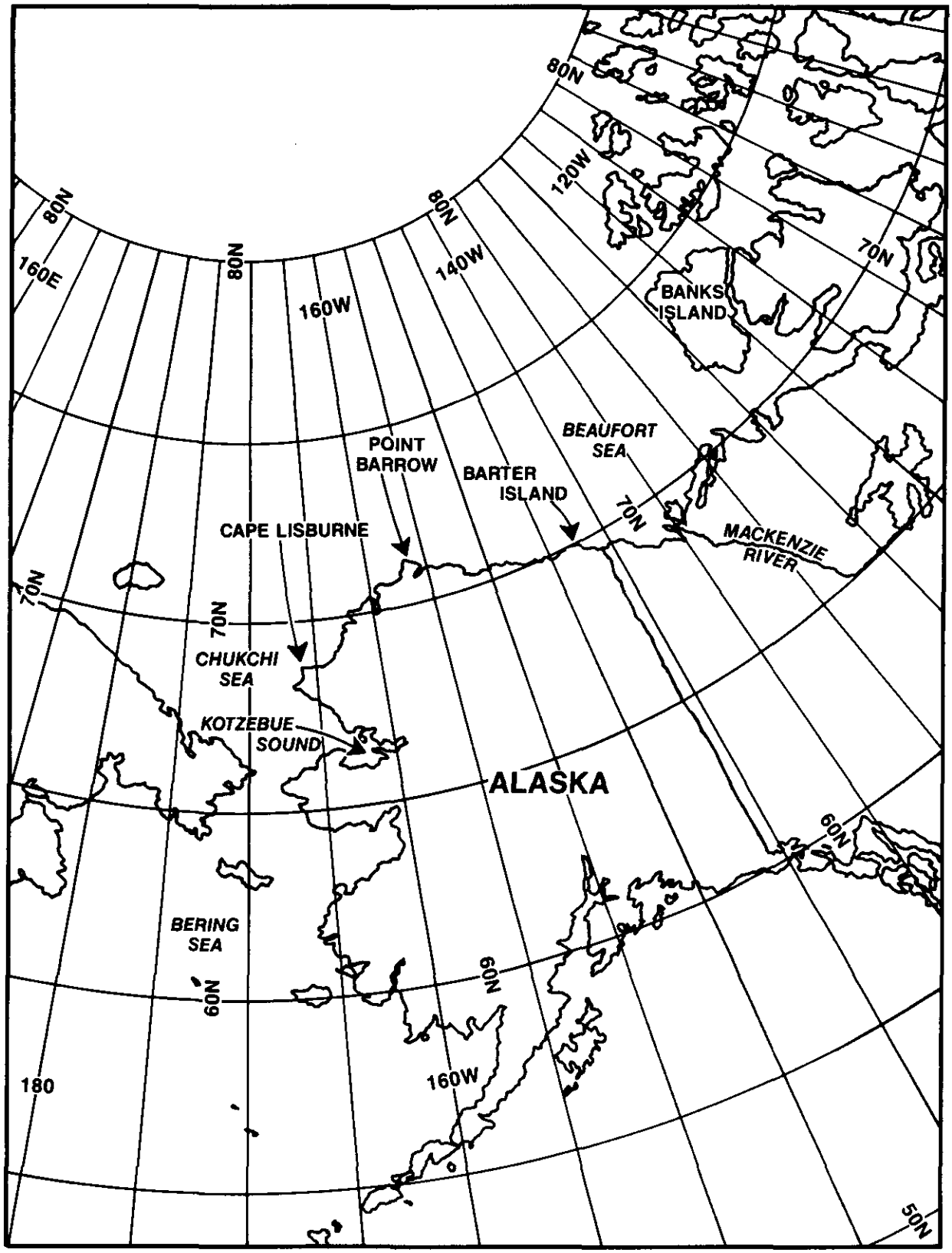

Figure 2-20. Chukchi Sea and Beaufort Sea Region.

2.5.3 Ice Distribution in the Canadian Archipelago

The Canadian Archipelago (Fig. 2-21) is a large area covering thousands of square miles with hundreds of narrow channels throughout the islands. Most of its waterways are completely covered with ice except for very short periods in the late summer or early fall. Many of these channels are never open to transit, even by an ice breaker. The most important factors affecting ice distribution in the archipelago are currents and weather conditions. For this discussion the archipelago is divided into four areas: the Queen Elizabeth Islands, Eureka Transit Route, McClure Strait to Lancaster Sound Route, and the Southern Archipelago.

Queen Elizabeth Islands

The predominant ice type throughout the Queen Elizabeth Islands area is multiyear ice. The exceptions are Wellington Channel, which is mostly winter ice with some polar ice, Jones Sound, and Central and Lower Eureka Sound, which are dominated by winter ice. Multiyear ice fringes all the island coasts, with the exception of the southern coasts of Melville Island, Bathurst Island, Cornwallis Island, and Devon Island where first year fast ice predominates. Freezeup starts in late August with puddles on the ice freezing. By mid-September the leads and cracks freeze.

Breakup and disintegration of the ice starts in March or April even though the maximum ice thickness is not reached until May. By late July much of the ice is rotten, but concentrations remain at eight-eighths. By mid-August the fast ice parts from the shore, and the concentration decreases to six- to seven-eighths in some areas. Navigation by ship is not feasible in the Queen Elizabeth Islands area at any time of the year.

Eureka Transit Route

The Eureka Transit Route is in the eastern portion of the Queen Elizabeth Islands and leads west along the south coast of Ellesmere Island and then north along the west coast of the island. The route goes through Jones Sound, which is dominated by first year floe ice and first year fast ice. The route then enters into Cardigan and Hell Gate Straits, which remain relatively ice free throughout the year because of swift currents. Some fast ice forms along the shorelines of these straits. Next, the route enters Norwegian Bay, which is dominated by multiyear floe ice with multiyear fast ice along the coastline. Finally the transit route enters Eureka Sound, which is dominated by first year and multiyear floe ice.

Freezeup begins in Jones Sound by mid-September, and it is usually frozen solid by the end of October. Cardigan and Hell Gate Straits do not freeze up due to swift currents. Norwegian Bay starts to freeze by late August and is completely consolidated by late September. Freezeup starts early in September in Eureka Sound and is completed by early October.

Because of the westerly winds, breakup in Jones Sound begins in July as ice loosens and moves into Baffin Bay. The minimum amount of ice is present in Jones Sound in late August or early September. Cardigan and Hell Gate Straits remain nearly ice free throughout the year, although heavy floes from Norwegian Bay can block the straits during any season.

Figure 2-21. Canadian Archipelago.

In favorable years in Norwegian Bay puddling and loosening of the ice begins in July, with navigation possible by mid-August. The ice in Eureka Sound starts to loosen in July, and navigation is possible by mid to late August.

Due to the swift, dangerous currents, coupled with multiyear ice floes, the greatest danger to ships is found in the Cardigan and Hell Gate Straits. The greatest resistance to navigation is the heavy multiyear ice concentrations in the upper two-thirds of Norwegian Bay. During the navigation season ice conditions are as follows: (1) Jones Sound is ice free to two-eighths ice coverage, with belts and patches of greater concentration; (2) Cardigan and Hell Gate Straits generally have less than one-eighth ice coverage, but the straits may

be blocked by multiyear floes for short periods; (3) Lower Norwegian Bay, five- to seven-eighths ice concentration; (4) Upper Norwegian Bay and Lower Eureka Sound, six- to eight-eighths ice coverage often under heavy pressure; and (5) Upper Eureka Sound, one- to two-eighths or less concentration with occasional influx of belts and patches of greater concentration and of multiyear ice floes from Nansen Sound.

McClure Strait to Lancaster Sound

This east-west waterway consists of Lancaster Sound in the east, then Barrow Strait, Viscount Melville Sound, and finally McClure Strait in the west. Ice conditions become progressively worse from east to west. Lancaster Sound and Barrow Strait are dominated by multiyear and first-year ice floes while Viscount Melville Sound and McClure Strait are dominated by heavy concentrations of multiyear ice floes.

Freezeup in Lancaster Sound and Barrow Strait usually begins in October, and they are frozen solid by early November. Viscount Melville Sound usually freezes by mid-September although ice may remain in motion until late November. McClure Strait usually remains clogged with ice all year.

The breakup in Lancaster Sound and Barrow Strait begins in late May; it is normally well advanced by mid-June in the eastern portion of Lancaster Sound and by late June in the remainder of the area. Viscount Melville Sound never completely clears of ice. The ice does loosen, however, and prevailing winds can pack it against the southern shores, leaving its northern shores open but not navigable until sometime in late August or September. McClure Strait usually remains choked with ice throughout the summer.

Navigation is normally possible in the eastern portion of this waterway and almost never possible in the west. The navigation season for Lancaster Sound and Barrow Strait is from mid-July to late September. The area is subject to an influx of ice from the west, and from Wellington Channel, so that even in the best season western Barrow Strait has a concentration of six- to seven-eighths ice. To the east, drifting belts and patches are common particularly along the southern coastal boundary. In Viscount Melville Sound and McClure Strait, navigation is not considered feasible west of Winter Harbor, and, in many years, it is not even possible to get to Winter Harbor.

Southern Archipelago

Nearly all of the waterways in this area are completely frozen for most of the year, but nearly all have at least a short period when they are open to navigation. All of the islands are rimmed with first year fast ice during the ice season. The central water areas remain the most congested with ice during the summer season. The following areas are dominated by first-year ice floes, with large amounts of multiyear ice also present: (1) Admiralty Inlet, (2) Prince Regent Inlet, (3) Gulf of Boothia, (4) Committee Bay, (5) Bellot Strait, (6) McClintock Channel, (7) Peel Sound, (8) Franklin Strait, (9) Victoria Strait, (10) James Ross Strait, and (11) Rae Strait. The following areas are dominated by first-year ice floes with little or no multiyear ice: (1) Simpson Strait, (2) Queen Maud Gulf, (3) Dease Strait, (4) Coronation Gulf, (5) Dolphin and Union Strait, and (6) Amundsen Gulf.

Freezeup starts throughout this area in early to late September, and by late October to mid-November the area is generally frozen solid.

Breakup varies considerably throughout the area. In Prince Regent Inlet ice starts to slacken late in June but rarely clears before mid-August. In Admiralty Inlet a great deal of ice occurs the year round, with large variations each year. Some years the minimum amount of ice occurs during August, and in other years a considerable amount of ice is present the entire season. The Gulf of Boothia clears later and has more ice than Prince Regent Inlet. Committee Bay usually contains six- to eight-eighths ice coverage the entire year. In Bellot Strait swift tidal currents keep some open water in this area all year. Sometimes the strait is open by mid-July but subject to great year-to-year variations. McClintock Channel is covered by six- to eight-eighths of ice the entire year. Shore leads occasionally exist from time to time along the west coast of Prince of Wales Island, while Victoria Strait is covered by four- to eight-eighths of ice throughout the year. Heavy polar floes often enter the strait from McClintock Channel. In Peel Sound cracks and puddling begin in early July, with the ice becoming very loose by mid-August. Breakup in the Franklin and James Ross Straits begins in June, and the ice melts and disappears by late August in good years. The western side of Amundsen Gulf breaks up in late June, and by late July the gulf becomes free of local ice. Dolphin and Union Strait ice starts to loosen in the early part of July, with the minimum amount of ice occurring during the last weeks of August. In Coronation Gulf the ice begins to break up in late June or early July and clears out by late August or early September. Ice in Queen Maud Gulf begins to loosen in late June. In July a wide shore lead develops along the shore of Victoria Island. Late August and early September is usually the most ice-free period. Simpson Strait ice loosens rapidly in July, with patches of open water appearing. The amount of clearance depends on the direction and strength of the winds. In Rae Strait rotting and puddling of the ice begins in late June or early July. Minimum ice conditions occur in late August or early September. Finally, in Dease Strait the ice loosens in June and by early August clears to a few eighths.

Most of the waterways of the Southern Archipelago have at least a short period when they are open to navigation. The periods of navigation are (1) Dease Strait and Coronation Gulf—late July to early August, (2) Dolphin and Union Strait, and Amundsen Gulf—mid-July, (3) Prince Regent Inlet, Gulf of Boothia, Committee Bay, Simpson Strait, and Queen Maud Gulf—mid-August to late September, (4) Admiralty Inlet and Bellot Strait—late August to mid-September, (5) Franklin Strait—late August to early September, and (6) James Ross Strait, Rae Strait, and Peel Sound—late August to early October. Victoria Strait and McClintock Channel are not navigable.

2.5.4 Ice Distribution in the Labrador Sea

Rarely does any remnant pack ice occur in the Labrador Sea (Fig. 2-22) before freezeup. During the freezeup a steady southward progression of the ice extent occurs. In late November fast ice begins to form in the northern coastal indentations. As December progresses, fast ice forms farther and farther south until by the end of December it has reached the southern coastal limit. At the same time that fast ice formation has progressed southward, it has progressed seaward. Depending on the latitude and the distribution of off-shore islands, it may extend 20 to 30 n mi (35–55 km) seaward from the coast proper. Throughout the winter and early spring it continues to grow in thickness. The pack ice or drift ice is brought southward from Baffin Bay in the Labrador Current, and, emanating from Hudson Strait,

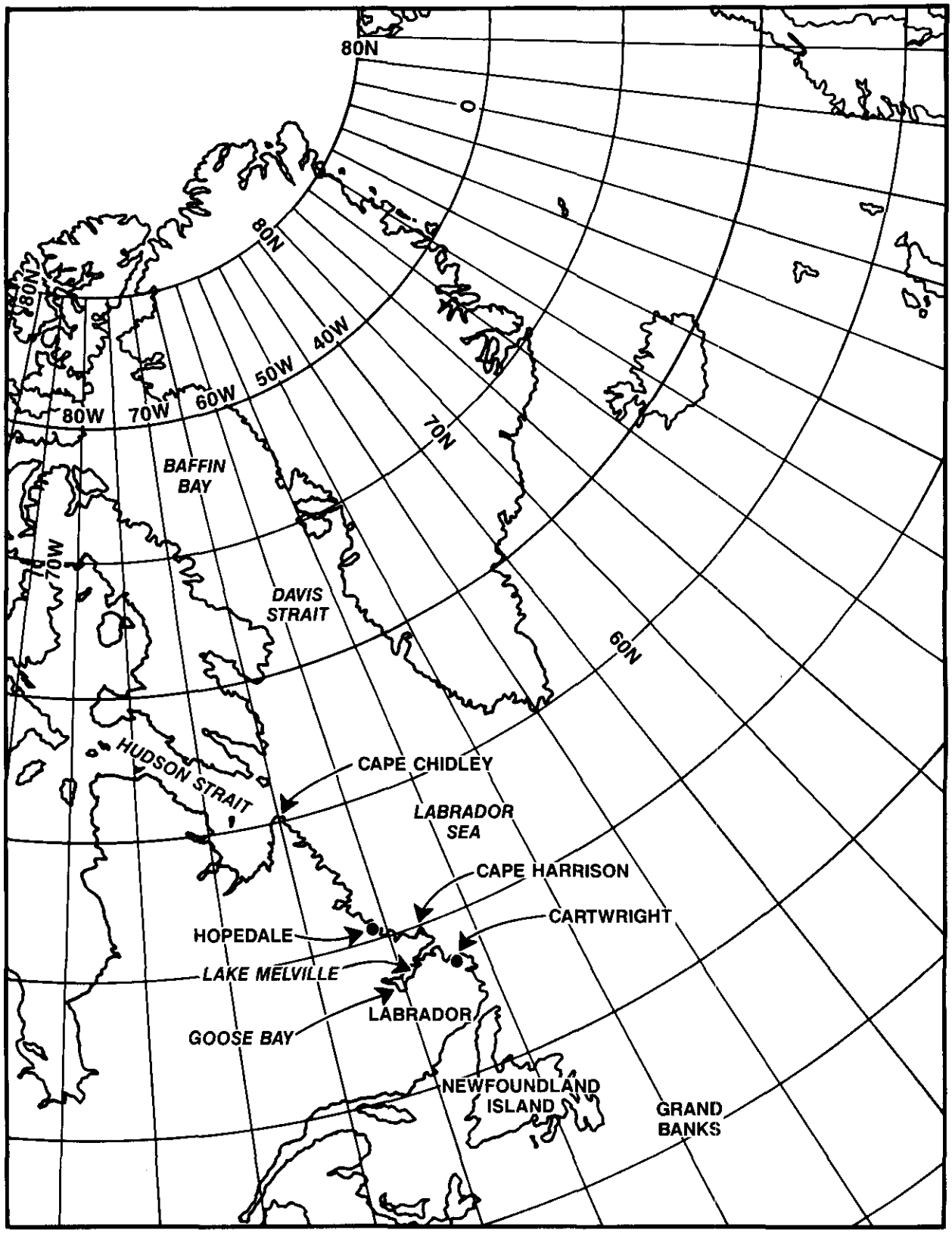

Figure 2-22. Labrador Sea Region.

it first appears off Cape Chidley in early December. By late December drift ice has reached the southern extremity of Labrador. The width of this stream of drift ice, its concentration, and general behavior depend on a number of factors. Among them are the amount of ice available from Baffin Bay and its tributary sounds, the rapidity with which the pack ice is released to the southward directed current, the speed of the Labrador Current, and the prevailing winds. The latter can be particularly effective in creating both favorable and unfavorable conditions for transit. Winds from the north or west tend to spread the ice by decreasing the concentration. Winds from the south or east tend to decrease the areal extent of the ice, hence increase the concentrations. With the advent of spring, the seaward extent of drift ice off the Labrador coast shows a marked increase until it reaches its maximum in May. In May, it extends seaward in the latitude of Cartwright for a distance of 120 to 140 n mi (220–260 km), narrowing rapidly toward the north until it extends only about 50 n mi (90 km) or less in the latitude of Cape Chidley.

Icebergs are normally encountered off the Labrador coast at any time of the year. The distribution of bergs throughout the coast waters of Labrador depends primarily on the number of bergs calved off the glaciers of western Greenland and conditions during the previous winter in Baffin Bay. The largest number of bergs are normally present during early spring.

Disintegration of the fast ice begins in March in the southern areas and extends into more northerly latitudes throughout April. Once disintegration has begun, it progresses quite rapidly, so that by the end of May nearly all coastal areas are free of fast ice. Hopedale and Cape Harrison are two significant areas that retain their fast ice longer. In late April and May the pack ice begins to disintegrate along the Newfoundland coast and along the entire ice edge south of 60 °N. During June great variability occurs in the position of the ice pack. Usually the concentration of the ice along the ice edge is open pack, with heavier concentration and fast ice along the coast. By the end of July the entire area south of 60 °N is normally ice free. In April a small ice area in the outer approaches to Goose Bay decreases to about three-eighths coverage. The fast ice in Lake Melville becomes well puddled in early or mid-May and melts by early June. The pack ice edge is, however, often south of the Goose Bay approaches through much of June, but by the end of June or the first of July, in a normal ice year, the approaches are ice free and ships can transit the area without the aid of an icebreaker.

Accessibility to the Labrador coast for shipping is largely dependent on two ice factors: (1) drift ice from the north and (2) local fast ice formation. The entire coast is normally ice free and navigable from late June or early July to late November and is normally closed to all shipping from late December to early June.

2.5.5 Ice Distribution in Baffin Bay and Davis Strait

In Baffin Bay and Davis Strait (refer to Fig. 2-12) a wide variation in ice conditions occurs with both time and locality. The major factors responsible for these variations are oceanographic features, latitude, and meteorological conditions. September is the month of least ice in this area. At that time, only scattered, rotten remnants of the Baffin ice pack, drifting small floes, polar ice cakes from the north, icebergs, BERGY BITS, and GROWLERS remain.

Baffin Bay

In October the freezing process begins for both the fast ice and pack ice. In October fast ice forms in Melville Bay, in the northern coastal indentations of Baffin Island, and the inner recesses of Cumberland Sound and Frobisher Bay. As the winter progresses, formation of ice is far from uniform, latitude for latitude. Fast ice continues its southward extent but much more rapidly along the Baffin Island coast than along the Greenland coast. By the end of November, fast ice extends the length of Baffin Island, but its southward extent along the Greenland coast is only slightly south of Melville Bay. The extent of both fast and pack ice continues to increase until the maximum is reached in March. At this time the fast ice along the Greenland Coast extends as far south as Disko Bay. Farther south, it is found only in the deep coastal indentations. Fast ice reaches its maximum seaward extent in the Melville Bay area and along the coast of Baffin Island from about Cape Christian northward. In the vicinity of Home Bay it frequently exceeds 30 n mi (55 km), and from there northward, the seaward edge is characterized by a pronounced shear line and heavy ridging. The remainder of the fast ice is relatively smooth except for glacial ice frozen in the fast ice. Off Cape Dyer the fast ice is often completely absent and rarely exceeds 1 n mi ($\approx$2 km) in extent.

Young pack ice first forms along a line from northeastern Baffin Island to the Cape York area, forming first in the west and then in the east. The growth and extent of the pack ice is similar to that of the fast ice as it forms first in the west and north and then grows eastward and southward. In November the drift ice has reached south of Cape Dyer, but in eastern Baffin Bay the southern limit is about 74 °N, leaving the eastern two-thirds ice free. The pack ice reaches its greatest extent in March. The southern limit of the drift ice at this time approximates a line from Sondre Stromfjord southwestward to within 50 mi east of Cape Chidley. The ice in the Baffin pack proper is in continual motion, hence the pack is composed of floes of all sizes and contains many cracks, leads, and areas of rafting and ridging. Its average thickness, excluding topographic features, is about 4 ft (1.2 m). That portion of the pack lying off the central coast of Greenland is weak and unstable even at the time of maximum extent and thickness.

The breakup starts in April though not necessarily in all areas, and follows the reverse pattern of the freezeup. This stage is more complex than the freezeup, however, because disintegration in one area may result in an increased ice concentration in another area. As disintegration begins, flaw leads appear in the Melville area and off the northern half of Baffin Island. The pack proper begins to break up so that the southward drift increases. The pack limit off the Greenland coast recedes northward and fast ice in the southern Greenland indentations, off the central Greenland coast and in the interior of Frobisher Bay, starts to break up and move out. By mid-June the pack south of 73 °N is well puddled, while the width of drift ice past Cape Dyer and the south Baffin coast has decreased. Greenland's coastal area is essentially ice free as far north as Upernavik, and the North About Route is open. The North About Route is a lead that normally extends through Melville Bay along a line connecting Nagssuaq, Holms Island, Thom Island, Bryants Island, Bushnans Island, and Cape York. While this lead is at its best, another lead, called the Middle Passage, is opening. This opening extends along a line connecting the Upernavik area to Cape York. By mid-July this lead is preferred over the North About Route, which normally becomes congested with ice as the fast ice of Melville Bay moves out. The fast

ice along the Baffin coast moves out about two weeks later, but ports are subject to drift ice from Lancaster Sound until mid-August. By late August, only a mass of rotten floes remains along the east coast of Baffin Island.

Icebergs in the Baffin Bay and Labrador Sea are calved from Greenland glaciers, particularly those along the west coast from Disko Island to 80°N. Because an iceberg's draft is generally significantly greater than the volume above water, icebergs are more responsive to ocean currents than to winds. Their distribution, therefore, follows closely the paths of prevailing currents. Icebergs from glaciers north of Disko Island are the main source of bergs encountered in the Grand Banks region. These icebergs drift with the currents that flow northward following the west Greenland coast, then turn westward and southward flowing along the coasts of Baffin Island and Labrador. Of the 20 major glaciers along the west Greenland coast, the two located in Disko Bay are estimated to contribute 28 percent of all bergs appearing in Baffin Bay and the western Labrador Sea. The greatest concentration of bergs occurs in this vicinity, particularly during June and July, when the fast ice breakup liberates hundreds of icebergs. The rugged Baffin Island and Labrador coastline, with its many indentations, trap many bergs that disintegrate in place. Estimates indicate that 1 iceberg in 20 survives the trip from west Greenland to Newfoundland. Those that do survive usually require about 3 years to complete the 1,800 n mi (3,335 km) journey.

An interesting feature of the sea ice distribution in the Baffin Bay area is the North Open water. This wide area has an ice concentration that is generally less than that of the surrounding regions. The North Open water seems to result from the constricting effect of Smith Sound, which shuts off the supply of ice from the north causing an ICE JAM in the vicinity of Cape Sabin. The southern limit of this jam is an arc convex to the north. To the south, ice is continually being removed by winds and currents, producing a zone of lower ice concentration. Here the ice is weak and unstable, and open water exists even in midwinter.

The extreme southwest coast of Greenland is subjected to an influx of hard polar ice known as *storis*. This ice has been brought from the polar regions in the East Greenland Current. The drifting storis first rounds Cape Farewell in December. Its amount and extent, both seaward and northward, increases until the maximum is reached in May. At this time the storis reaches as far north as Godthaab and extends approximately 70 to 100 n mi (130–185 km) seaward in the vicinity of Julianehaab. By September little or no storis is drifting around the southern tip of Greenland.

Frobisher Bay

In early October young ice begins to form along the entire coastal area of Frobisher Bay, and tidal action continually breaks it up. By late October or early November enough ice has been deposited along the shore to seriously hamper loading or lighterage for shipping operations. By mid-November the upper bay is solidly frozen and the southeastern half of the bay is covered with young ice; but the offshore approaches are essentially free of hampering ice conditions. As the fast ice continues to grow and is subjected to wide tidal ranges, large quantities are beached and heavy ridging occurs. Another factor that contributes to the heavy ridging is the extremely low temperatures to which the ice is subjected. The lower bay and approaches become blocked by drifting sea ice in December, with concentrations of seven- to eight-eighths by January. This sea ice is normally heavily ridged. The fast ice continues to thicken, reaching a maximum in April or May.

By late May or early June melt and disintegration begin, with scattered puddles and tidal cracks appearing. By July the fast ice is in the advanced stages of disintegration, but the lower bay and approaches remain blocked by drifting sea ice. By the end of July icebreaker entry is possible, and by mid-August unescorted entry is possible. In September the lower bay and approaches are essentially ice free except for icebergs, bergy bits, and growlers, which are present throughout the year.

Although ice conditions in Frobisher Bay vary greatly from year to year, normally the bay is open to icebreaker entry in late July and to unescorted entry in August. The bay generally closes to unescorted shipping by mid-October and to icebreaker entry by mid-November. Consequently, the best month for shipping is September.

Thule to Alert Route

The route between Thule and Alert (Fig. 2-23) is never ice free and is not considered safe for navigation by anything but an icebreaker. North of Smith Sound the passage is covered by five- to seven-eighths of heavy polar pack ice even in the best month of August. Throughout this area the wind is the major factor in determining the transit route and its dangers. In this north-south waterway, from the breakup in July to the freezeup in September, a changing wind direction will cause the leads to shift from coast to coast. A strong southerly wind will open a lead north of Robeson Channel permitting easy transit around Cape Sheridan to Alert, but a northerly wind will keep this area so congested with ice from the Lincoln Sea that transit of this area may be hazardous. These rapidly changing ice conditions can make the passage impossible to navigate even by an icebreaker. Ice conditions throughout this route are progressively worse from south to north and the navigation season is progressively shorter. Alert, at best, is accessible for only a few weeks, with refreezing starting in late August.

Thule and Its Approaches

Freezeup begins in October with the formation of grease ice that slowly thickens to young ice, becoming fast to the shore. Changing tides and foehn winds (warm katabatic winds) can change the ice concentrations rapidly during this time and may move the ice totally out of the bay. With a shift in wind the ice can also move rapidly back into the bay. In November or December the ice freezes permanently and increases to 3 ft (1 m) thick by the end of December. Tidal cracks form next to the shoreline of islands and the mainland. The ice continues to thicken to about 70 in ($\approx$ 180 cm) in late April. The ice in the bay around Thule is quite smooth with a snow cover of 1 to 3 ft (0.3–0.9 m), which is blown off the adjacent mountains and icecap.

Breakup in the bay begins in May as puddles and cracks start to form. Strong easterly winds can move most or all of the ice out of the bay as early as mid-June. Absence of these winds may result in ice lingering in the bay as late as mid-July. Also, ice blown out of the bay could move back into the bay if a wind shift occurs. From mid-July through September, after the fast ice is blown out of the bay, the area is essentially ice free. During this period, however, an increase in icebergs, bergy bits, and growlers occurs.

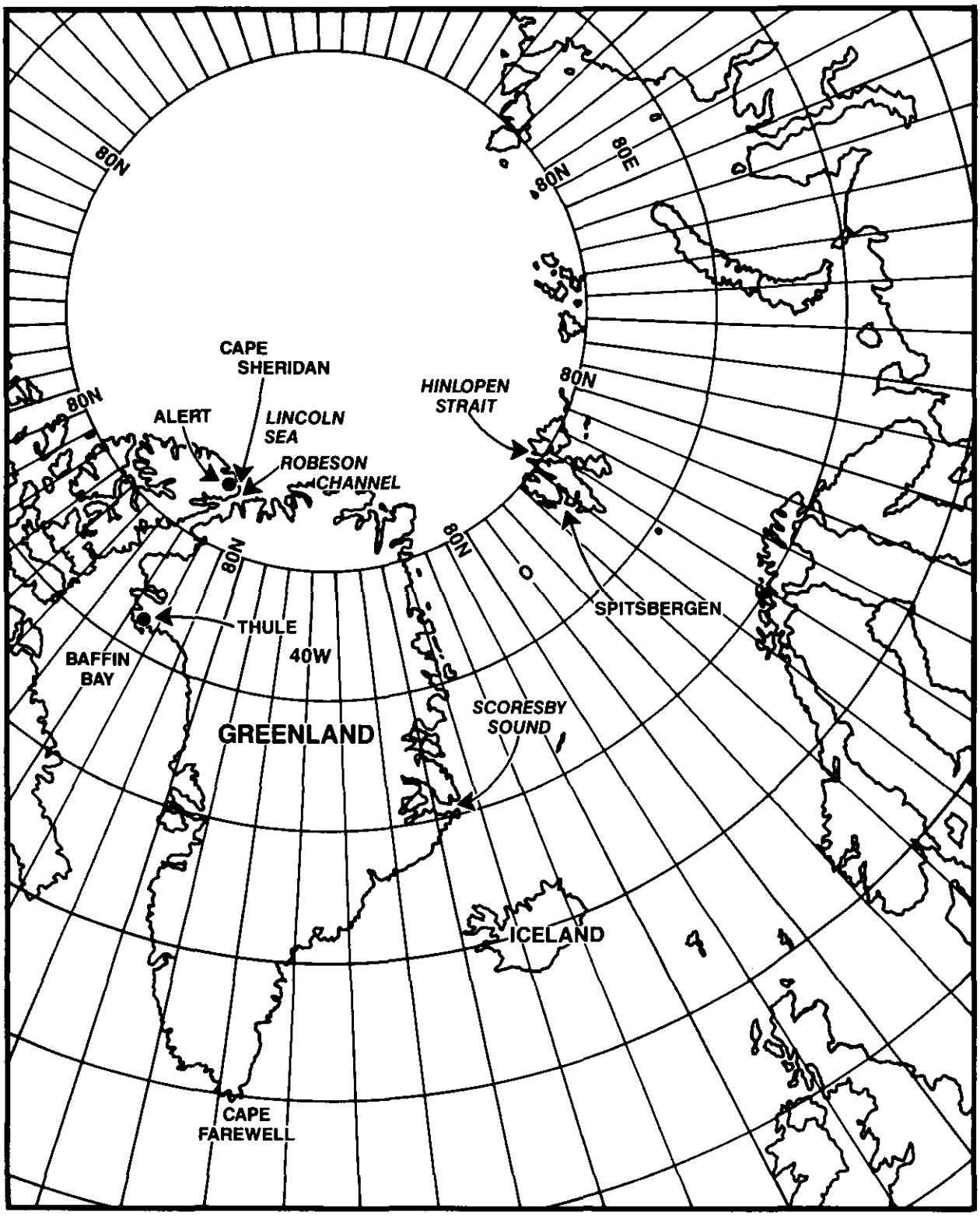

Figure 2-23. Greenland/Iceland Region.

Sondre Stromfjord

Fast ice formation in the fjord is the only problem concerning ship transit into Sondre Stromfjord. Fast ice growth is usually sufficient to halt unescorted shipping by late December, but with icebreaker support transit may be possible throughout the winter. By January or February, fast ice in the upper one-third of the fjord reaches a maximum thickness of about 60 in ($\approx$ 150 cm), while in the central third of the fjord the maximum thickness is about 25 in ($\approx$ 65 cm). This difference may be due to foehn winds in the lower fjord. Tidal ranges of 8 to 11 ft (2.5–3.5 m) help keep the ice weak and elastic throughout the winter.

Breakup occurs from March through May, and the ice becomes heavily puddled and rotten by the end of the period. In late May an icebreaker usually will make one or more runs up the fjord to break up the fast ice. The ice fractured in this manner will either melt or move out in two to three weeks. Icebergs may be encountered off the entrance to Sondre Stromfjord, however, none in the fjord. The fjord is generally ice free from mid-June through November or early December.

2.5.6 Ice Distribution in the East Greenland, Iceland, and Spitsbergen Areas

East Greenland

The east Greenland coastal area is regarded as one of the most inaccessible areas in the world because of the continual flow of multiyear polar ice from the Arctic Ocean via the East Greenland Current. Approximately 95 percent of the total polar ice expelled from the Arctic Ocean each year is carried southward in this strong current. Throughout the year this mass of drifting ice extends 100 to 300 n mi (185–555 km) offshore to the north of Scoresby Sound. South of Scoresby Sound, the maximum offshore extent is reached in the spring, when the ice may extend nearly 200 n mi (370 km) offshore. The minimum extent in this area occurs in August and September, when only belts and patches are present. The drifting multiyear ice is at its maximum extent from December through May, when it drifts around Cape Farewell.

Most of the fast ice along this coast is found in protected coastal fjords, bays, and sounds (sunds). South of Scoresby Sound, this ice is cleared out of these indentations many times throughout the winter due to the foehn wind effect.

Navigation along the east coast of Greenland, even south of Scoresby Sound, has only been attempted by extremely skilled and adventurous seamen. Icebreaker entry into Scoresby Sound should be possible, however, from early August to early or mid-October, but it is considered extremely hazardous. A limited number of unescorted entries are made each year by skilled Danish pilots in ships of special design and construction.

Iceland

Iceland is generally ice free throughout the year except for fast ice extending to the outer harbor entrances on the north coast and for weak unstable ice in bays along the southern coast. Even when the pack ice off the east Greenland coast drifts to its maximum extent,

normally a 50 n mi (90 km) wide area of open water exists between Iceland and the ice pack. On a few occasions, however, the ice has drifted down and touched the north coast of Iceland for a short period of time.

Spitsbergen

Ice conditions along the south and west coasts of Spitsbergen differ drastically from those on the north and east coasts. The north and east coasts have heavy fast ice formations during the winter and are usually subject to closing by polar pack ice throughout the year. The south and west coasts have only a narrow band of fast ice in winter and some areas are ice free all year. Under normal conditions the north coast is navigable by late July or early August, but the east coast does not open until mid to late August. In the area of the Hinlopen Strait usually some ice occurs throughout the year.

2.5.7 Ice Distribution in the Seas of the Soviet Union

In the ice pack off the north coast of the U.S.S.R., a conglomeration of all types of ice occurs. The predominant ice within the coastal seas is winter ice. The North Atlantic Drift is a warm current that enables the island of Iceland to have a fairly temperate climate for its latitude and also causes the Barents Sea (refer to Fig. 2-1) to be the most navigable of the U.S.S.R. polar seas. During the winter months, the entire coastline from the Chukchi Sea to the Kara Sea is frozen fast, and only the western part of the Barents Sea is found to be ice free. Conditions remain as such during the winter months until June, when the great rivers of the U.S.S.R., which empty into the Arctic Ocean (the Ob, Yenisei, Lena, and Kolyma), begin to break up in their southern areas and cause great amounts of fresh meltwater to run over the top of the downstream river ice, and carry great amounts of dirty water to their mouths and out onto the sea ice. This darker discoloring of the ice reduces its albedo and increases its ability to absorb heat; thus it melts more rapidly, so that by mid-July, a narrow shore lead exists along the coastline. The lead is discontinuous, but by August a navigable area extends along the entire coast. This navigable area is open to shipping until October. The freezeup takes place first in the Chukchi and Laptev Seas, as the increasing northerly and northeasterly winds push the Arctic ice pack onto the shore. This occurrence is followed by the closing of the East Siberian Sea and then the Kara Sea in November. In December, the strait between Novaya Zemlya and the mainland is closed by winter ice, and the freezeup is almost complete except for the formation of fast ice in the protected bays of the Barents Sea.

Icebergs calved from glaciers on the islands of Svalbard, Franz Josef Land, Novaya Zemlya, and Severnaya Zemlya are small in number and structure, owing to the shallow glacial ice. Bergs from these islands calve mainly on the north side; they tend to move with the prevailing currents but seldom are encountered near the north coast of the U.S.S.R. In the Barents Sea maximum iceberg occurrence is coincident with the withdrawal of the pack ice northward, with the greatest number found near the ice edge.

Barents Sea

The predominate forms of ice in the Barents Sea (Fig. 2-24) are winter and young ice, with some polar ice found occasionally between Franz Josef Land and Spitsbergen. During the winter and spring the Bear Island Current carries colder polar water and some polar ice into the vicinity of Bear Island.

In average ice years the entire west coast of Novaya Zemlya will be icebound from November through May. In winter the bays and gulfs of the eastern Barents Sea become icebound. The deeper portion of the sea is covered with drift ice consisting of both hummocked and level ice floes. The hummocks are usually 5 to 15 ft (1.5–4.5 m) in height. These hummocky floes normally come from the Polar Basin area. The ice reaches its greatest extent in March and April. Rapid melting takes place from May to August, after which the process decreases and freezing commences. In early June, during very mild ice years, a small portion of the southwest coast may be free of ice. Beginning in mid-July through October the west coast of Novaya Zemlya is normally ice free.

The Norwegian and North Cape Currents keep the Norwegian coast ice free in all months, except for the ice formed within some of the fjords. Ice is no hindrance to navigation within about 400 n mi (740 km) of the west Norwegian coast and 150 n mi (280 km) of the north Norwegian coast. The Norwegian coast and most of the Murmansk coast are kept free of ice by the warm Atlantic water throughout the year.

White Sea

The White Sea is dominated by winter fast ice and winter pack ice. Freezeup starts in October in the deep bays and usually forms a continuous strip of thin ice by December. The whole interior of the sea is filled with drift ice of varying strengths and thicknesses. Depending on wind conditions in the White Sea the ice will either break up and raft, or remain level. Ice reaches its greatest concentration during February and March. Breakup of the fast ice begins in April, and by May the drift ice in the middle of the sea melts rapidly so that by June little drift ice is left in the White Sea. At Archangel the average ice lasts from early to mid-November to early to mid-May. Very little ice drifts from the White Sea into the Barents Sea and any that does melts in a short time in the warmer waters of the Murmansk coast current. Generally, the shipping season in the White Sea is from June to late September.

Kara Sea and Its Approaches

Winter ice is the predominate type in the Kara Sea, with some polar ice along the east coast of Novaya Zemlya. Freezeup starts in late September, and the Kara Sea will be frozen solid by December. The ice comes under considerable pressure, resulting in ridges piled as high as 25 ft (7.5 m). This ice drifts with the currents or becomes stranded on shoals where it can remain for several years. The ice begins to break up in June and continues throughout the summer, with the minimum amount of ice occurring in September.

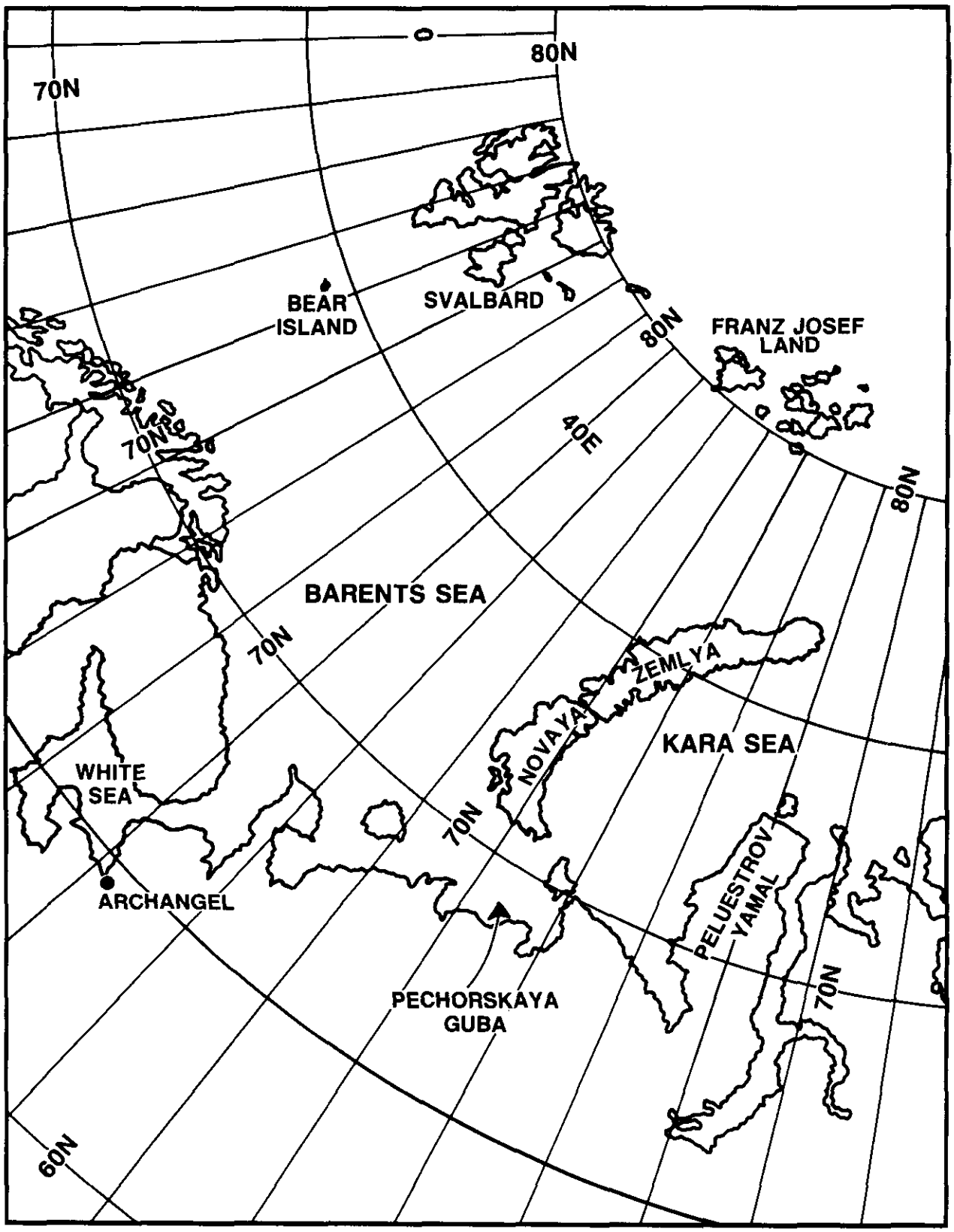

Figure 2-24. Barents Sea and Kara Sea Region.

Generally the area is navagable from July through October, with the best conditions occurring in late September. Navigation is the most difficult in the southwestern section of the Kara Sea, in the bay between Novaya Zemlya and Peluestrov Yamal, in the straits between the Kara Sea and the Barents Sea and Pechorskaya Guba. This difficulty is due primarily to the counterclockwise current regime of the Kara Sea, which concentrates ice in the southwestern section.

Laptev Sea

The Laptev Sea (Fig. 2-25) is predominated by winter ice with varying amounts of polar ice. Ice formation usually begins along the coastal areas of the offshore islands in mid-September due to seasonal cooling. Generally, the Borisa Vilkitskogo Strait, between the Kara Sea and Laptev Sea, contains compact fields of ice by mid-October, and the straits in the eastern part of the sea are completely ice covered in November. From November through June the entire sea normally is dominated by compact ICE FIELDS. Rapid changes in ice conditions take place in early July, with the introduction of the relatively warm river water and rapid decrease in ice concentration occurring alongshore. By early August open water exists along the southern shores of the sea. The straits are subject to temporary closing in all months because of the general southwesterly drift of ice into the area, which is associated with counterclockwise currents in the sea.

The best navigation period is July through late September. Navigation is considered most difficult along the coast of the Taimyr Peninsula and in Borisa Vilkitskogo Strait. Here the most severe ice conditions are found. The coastal ice is carried eastward by currents toward Cape Chelyuskin. Polar pack ice is carried southeastward along the east coast of Severnaya Zemlya to the vicinity of the Taimyr Peninsula. Heavy pack ice accumulates in the center of the Laptev Sea, forcing the shipping lane close in along the coast of the Taimyr Peninsula, but the southern and southeastern parts of the sea are usually ice free. The surface currents here have a great influence on the distribution of ice.

East Siberian Sea

The East Siberian Sea (Fig. 2-25) is dominated by winter ice with some polar ice. The coastal waters usually freeze from west to east. Ice formation usually begins in Dmitriya Laptev Strait, between the Laptev and East Siberian Seas, in September, near Medvezhi Ostrova in October, and near Cape Shelagski at the beginning of November. Normally this area is closed to shipping by October and frozen over by November. Thawing usually begins in May but the breakup of ice does not normally occur until July. The winter ice melts rapidly as the result of summer heating and the discharge of warm water from the numerous Siberian rivers. Between the Indigirka and Kolyma Rivers ice breakup occurs within the first two weeks of July, near Cape Shelagski about the third week of July, and near Cape Schmidt about the last week in July.

The polar pack ice is prevented from spreading southward into the East Siberian Sea by the New Siberian Islands, with the result that the East Siberian Sea coast is nearly ice free during the summer season. Fast ice extends northward from the mainland to the 15 fathom ($\approx$27 m) contour and includes the entire area of the New Siberian Islands. North of this fast ice lies continuously moving drift ice, whose movement is predominantly from the southeast toward the west-northwest. When strong southerly winds prevail, wide polynyi

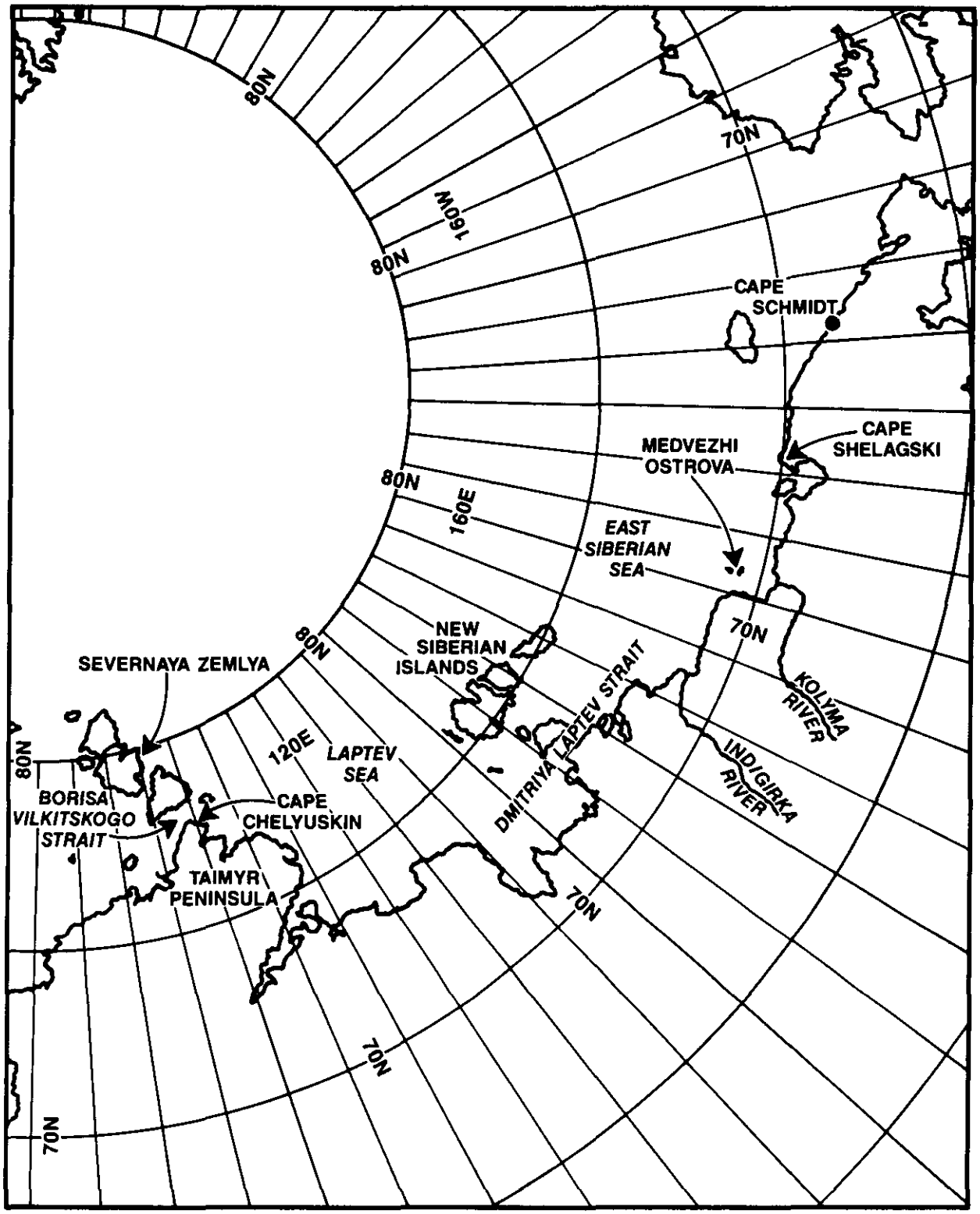

Figure 2-25. Laptev Sea and East Siberian Sea Region.

form on the seaward side of the fast ice. When strong northerly winds prevail, these polynyi become filled with drift ice, which eventually is piled high along the edge of the fast ice. In the deeper, eastern part of the East Siberian Sea, this process is likely to occur closer to the coast, which may result in belts of ice hills that finally come to rest on the bottom. These ice hills are known as stamukhas. The limit of their extent is usually between the 10- to 15-fathom ($\approx$ 18–27 m) depth curves. In the summer, ice-free water is found between the stamukhas and the coast, providing a fine shelter for ships from the drift ice still present in the northern part of the sea. This area also may be used as an anchorage by a ship forced to winter over. The navigation season in the East Siberian Sea is from July to September, with minimum ice conditions occurring in late September.

2.6 Ocean Currents

In addition to winds, ocean currents have a major influence on the motion of the ice. Several sources of oceanic currents exist causing the currents to be quite complex at times. The motion of the water due to tides can also be complex, particularly in shallow and long embayments. (This short section does not attempt a complete treatment of the subject.)

Several centuries of observations have yielded considerable knowledge of the major current systems in the Earth's oceans. Yet, as late as 1961, a major and important current in the equatorial Pacific Ocean was discovered. Although published charts of oceanic currents appear to imply steady and constant currents, this is not really the case. These charts represent averages and generalizations. The accompanying chart (Fig. 2-26) shows the known current systems in the Arctic. Where data are available, the magnitude of these currents is given in knots as well as the direction of the current.

The magnitudes of oceanic currents are not large when compared to wind velocities. Nevertheless, they are much more constant and, therefore, can add a significant component to ice drift, especially over periods of time greater than one day.

Figure 2-26. Surface Currents of the Arctic.