Chapter 2

Physical/Geographical Characteristics of the Arctic

Contents

2.1. Introduction

The vast region of the Arctic extends across northern North America, northern Europe and northern Asia, taking in eight countries and the expanses of sea and ocean in between. The terrestrial, freshwater and marine environments throughout this area exhibit considerable variation in climate, meteorology and physical geography. This chapter describes this diversity as a background to discussions on contaminants and other stressors in these environments.

2.2. Definitions of the Arctic region

The Arctic is often delimited by the Arctic Circle (66°32'N) (Figure 2·1), which approximates the southern boundary of the midnight sun. Such a definition, however, is simplistic, given variations in temperature, presence of mountain ranges, distribution of large bodies of water, and differences in permafrost occurrence. Outlined below are some definitions of the Arctic region which take into account physical, geographical and/or ecological characteristics. Following these, the Arctic region, as defined for the purposes of the AMAP assessment, is discussed.

2.2.1. Climate boundaries

On the basis of temperature, the Arctic is defined as the area north of the 10°C July isotherm, i.e., north of the region which has a mean July temperature of 10°C (Figure 2·1) (Linell and Tedrow 1981, Stonehouse 1989, Woo and Gregor 1992). This isotherm encloses the Arctic Ocean, Greenland, Svalbard, most of Iceland and the northern coasts and islands of Russia, Canada and Alaska (Stonehouse 1989, European Climate Support Network and National Meteorological Services 1995). In the Atlantic Ocean west of Norway, the heat transport of the North Atlantic Current (Gulf Stream extension) deflects this isotherm northward so that only the northernmost parts of Scandinavia are included. Cold water and air from the Arctic Ocean Basin in turn push the 10°C isotherm southward in the region of North America and northeast Asia, taking in northeastern Labrador, northern Quebec, Hudson Bay, central Kamchatka, and much of the Bering Sea (Stonehouse 1989).

Another geographical indicator of the Arctic region that is partially determined by climate is the presence of permafrost (Barry and Ives 1974). The southern boundary of continuous permafrost is shown in Figure 2·11.

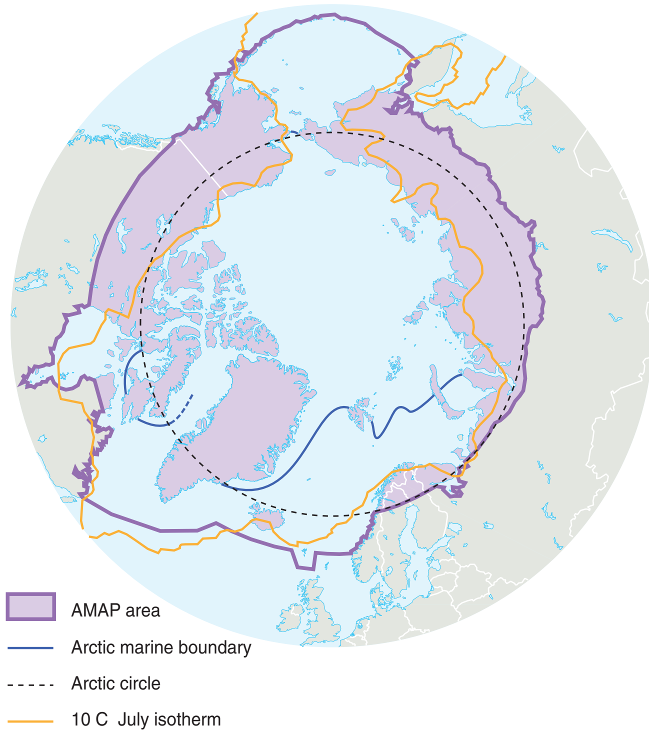

Figure 2·1. The Arctic as defined by temperature (after Stonehouse 1989), and the Arctic marine boundary, also showing the boundary of the AMAP assessment area.

2.2.2. Vegetation boundaries

A floristic boundary used to delimit the terrestrial Arctic is the treeline (Figure 2·2) (Linell and Tedrow 1981). Simply defined, the treeline is the northern limit beyond which trees do not grow. More accurately, it is a transition zone between

Figure 2·2. Arctic and subarctic floristic boundaries (Bliss 1981, Linell and Tedrow 1981, Nordic Council of Ministers 1996).

continuous boreal forest and tundra, with isolated stands of trees. In North America, the tundra-forest boundary is a narrow band, but in Eurasia this region can be up to 300 km wide (Stonehouse 1989). It corresponds with the climatic zone where the Arctic air masses meet the air masses originating from the south over the subarctic (Bryson 1966 in Larsen 1973).

The treeline roughly coincides with the 10°C July isotherm (Stonehouse 1989, Woo and Gregor 1992). However, in some areas, the treeline lies 100-200 km south of the isotherm, adding western Alaska and the western Aleutians to the Arctic region (Stonehouse 1989).

The Arctic region is often divided by ecologists into the High Arctic and the Low Arctic as shown in Figure 2·2 and described in chapter 4, section 4.4.1. South of the Arctic is the subarctic, the region lying between the closed-canopy boreal forests to the south and the treeline to the north (Figure 2·2). This region, which combines characteristics of both the boreal forest and the Arctic tundra, is also referred to as the taiga or forest tundra. The southern boundary of the subarctic generally corresponds with the southern limits of discontinuous and sporadic permafrost. Thus, permafrost is present throughout most of the subarctic (Linell and Tedrow 1981).

2.2.3. Marine boundary

Based on oceanographic characteristics, the marine boundary of the Arctic is situated along the convergence of cool, less saline surface waters from the Arctic Ocean and warmer, saltier waters from oceans to the south (Figure 2·1). In the eastern Canadian Arctic Archipelago, this zone exists approximately along a latitude of 63°N, and swings north between Baffin Island and the west coast of Greenland. Off the east coast of Greenland, the marine boundary lies at approximately 65°N. The warming effect of the North Atlantic Current deflects this boundary north of 80°N west of Spitsbergen, while it moves southward in the Barents Sea to 76°N. Warm Pacific water passing through the Bering Strait meets the Arctic Ocean water at approximately 72°N, from Wrangel Island in the west to Amundsen Gulf in the east (Stonehouse 1989). However, once it passes through the Bering Strait, Pacific water begins to undergo modification on the broad Chukchi shelf due to ice-related processes (freezing, melting, cooling) and the addition of runoff. Modified water becomes incorporated into the surface mixed layer or subducts and flows down the undersea canyons to contribute to the halocline. Recognizing the difficulty of assigning a distinct boundary separating Pacific water from Arctic water, the boundary is arbitrarily drawn across Bering Strait as the point at which modification is likely to commence. Similarly, for the purposes of the AMAP assessment, and recognizing other factors which may be used to define the Arctic marine area, such as Arctic marine biology and sea ice cover, the AMAP marine area to the south of the region as defined above also includes: Davis Strait, the Labrador Sea and Hudson Bay; the Greenland, Iceland, Norwegian, Barents, Kara and White Seas; and the Bering Sea.

2.2.4. Geographical coverage of the AMAP assessment

Given the different definitions of the Arctic, based on physical-geographical characteristics as described above, and those based on political and administrative considerations within different countries, no simple delineation of the Arctic region was applicable for the purposes of the AMAP assessment. To establish a geographical context for the AMAP assessment, therefore, a regional extent was defined based on a compromise among various definitions. This incorporates elements of the Arctic Circle, political boundaries, vegetation boundaries, permafrost limits, and major oceanographic features. The region covered by AMAP is, therefore, essentially the terrestrial and marine areas north of the Arctic Circle (66°32'N), and north of 62°N in Asia and 60°N in North America, modified to include the marine areas north of the Aleutian chain, Hudson Bay, and parts of the North Atlantic Ocean including the Labrador Sea.

As stated above, the AMAP boundary was established to provide a geographical context for the assessment, in particular source-related assessment issues, i.e., consideration of sources within and outside the Arctic. The relevance of the AMAP boundary (Figure 2·1) varies when considering different issues, and it has therefore been applied accordingly. Thus, contaminant levels in biota are addressed in relation to the geographical occurrence of the species concerned; demographic data are discussed in relation to administrative regions on which, for example, census data are collected.

2.3. Climate and meteorology

2.3.1. Climate

The polar areas are characterized by low air temperatures. This is because they receive, on an annual basis, less solar radiation than other parts of the world. However, the radiation levels vary greatly depending on the season. In the winter months, there is a total lack of incoming solar radiation, while in the summer, the poles receive higher levels of solar radiation than any other place on Earth.

The annual amount of solar radiation received is less than that which is lost to space by long-wave radiation, since a large part of the solar radiation that reaches the Earth is reflected by extensive cloud, snow and ice cover. This radiation imbalance produces low temperatures and results in a redistribution of heat from southern latitudes via air and ocean currents (Varjo and Tietze 1987). This energy regime is the fundamental factor driving the Arctic climate.

The effect of macro-scale topography of the Earth's surface, in particular the distribution of land, sea and mountains, is important for regional and local climatic conditions in the Arctic. The frequency and the preferred tracks of the persistent Pacific and Atlantic low-pressure systems and the position of the persistent high-pressure systems not only play an important role in the existence of the regional and local climates in the Arctic, but also link the Arctic climatic system to the world climatic system.

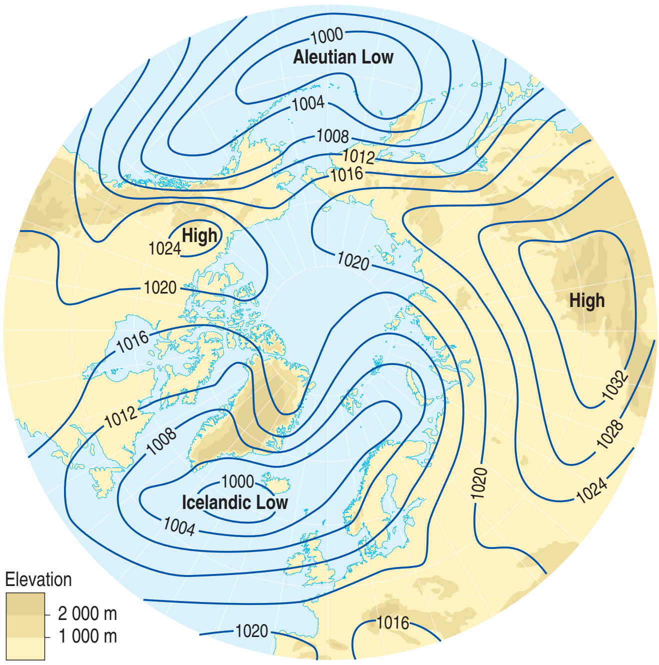

Figure 2·3. Mean atmospheric sea-level pressure (mb) in the Arctic in January (after Barry and Hare 1974).

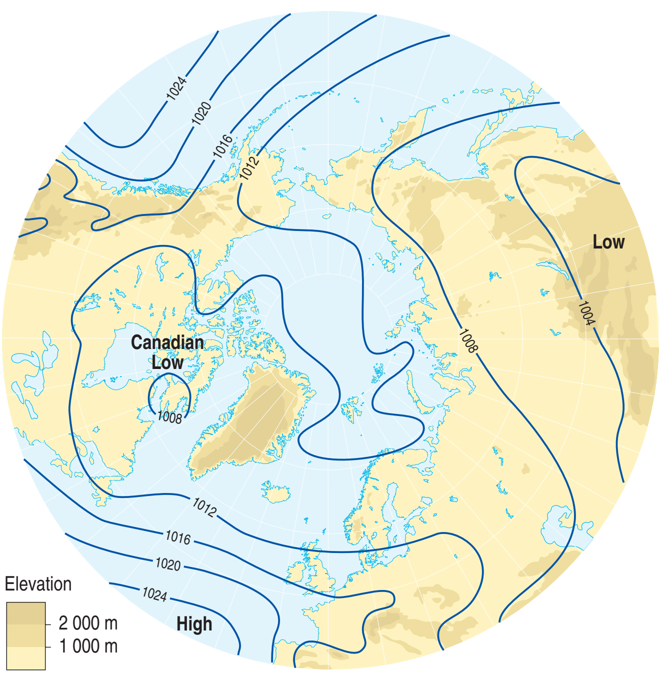

Figure 2·4. Mean atmospheric sea-level pressure (mb) in the Arctic in July (after Barry and Hare 1974).

2.3.2. Atmospheric circulation

The pattern of mean sea-level pressure for January in the Arctic shows a low-pressure area over the North Atlantic Ocean around southern Greenland and Iceland (Icelandic Low) and a low-pressure area over the Pacific Ocean south of the Aleutians (Aleutian Low) (Figure 2·3). The influence of the Icelandic Low extends to the North Pole, while that of the Aleutian Low is effectively blocked by the mountains of Alaska and northeast Siberia (Barry and Hare 1974). The large-scale air circulation over the North Atlantic Ocean is determined by the Icelandic Low and the high-pressure areas over Greenland and the Central Arctic Basin. The prevailing winds are westerly or southwesterly between Iceland and Scandinavia, transporting warm and humid air from lower latitudes toward the Arctic. Farther north, the circulation is generally anticyclonic around the pole with easterly and northeasterly prevailing winds. Strong winds over large areas are associated with intense depressions. These winds are most frequent in the Atlantic sector of the Arctic where they follow a track from Iceland to the Barents Sea in the winter. In January, the anticyclones are most frequent and strongest over Siberia and Alaska/Yukon, with a weaker system over the central Arctic Basin and Greenland.

In July, the Aleutian Low disappears and the low-pressure area off Iceland shifts to southern Baffin Island in Canada (Canadian Low) (Figure 2·4). The pressure is low over Central Siberia and a weak ridge of high pressure over the Arctic Ocean separates this low from the Canadian Low. High-pressure areas are located around the North Pole and north of the Pacific Ocean (Barry and Hare 1974). Atmospheric circulation patterns are further discussed in chapter 3, section 3.2.

2.3.3. Meteorological conditions

2.3.3.1. Air temperature

Climate conditions in the Arctic are divided into maritime and continental subtypes. A maritime climate is characteristic of Iceland, the Norwegian coast, and the adjoining parts of Russia. These areas have moderate, stormy winters. The summers are cloudy, but mild with mean temperatures of about 10°C. The average winter temperatures are –2°C to 1°C in the Icelandic lowland, –2°C at Bodø on the Norwegian coast, and –11°C at Murmansk on the Russia coast (Barry and Chorley 1992, EEA 1996). Figure 2·5 shows the distribution of January and July air temperatures in the Arctic.

A maritime climate is also found directly along the Alaskan coast. This zone is very narrow because of the mountains of the Alaska and Coastal Ranges. Winters here are moderate and the summers are mild, but cloudy. The average temperature at Anchorage ranges from –5°C in winter to 10°C in summer.

Continental climate is found in the interior of the Arctic from northern Scandinavia toward Siberia, and from eastern Alaska toward the Canadian Arctic Archipelago, with much lower precipitation and significant differences between summer and winter conditions (July means of 5-10°C; January means of –20° to –40°C) (Prik 1959). Over the ice-covered Arctic Ocean, both the ice and the underlying sea have a regulating effect on temperature. The minimum air temperature is moderated by heat conducted from seawater below the ice. Generally, in the central Arctic, the average temperature is between –30° and –35°C in winter and between 0° and 2°C in summer.

Moving depressions, and heat transported by ocean currents, have a warming effect on the climate which becomes

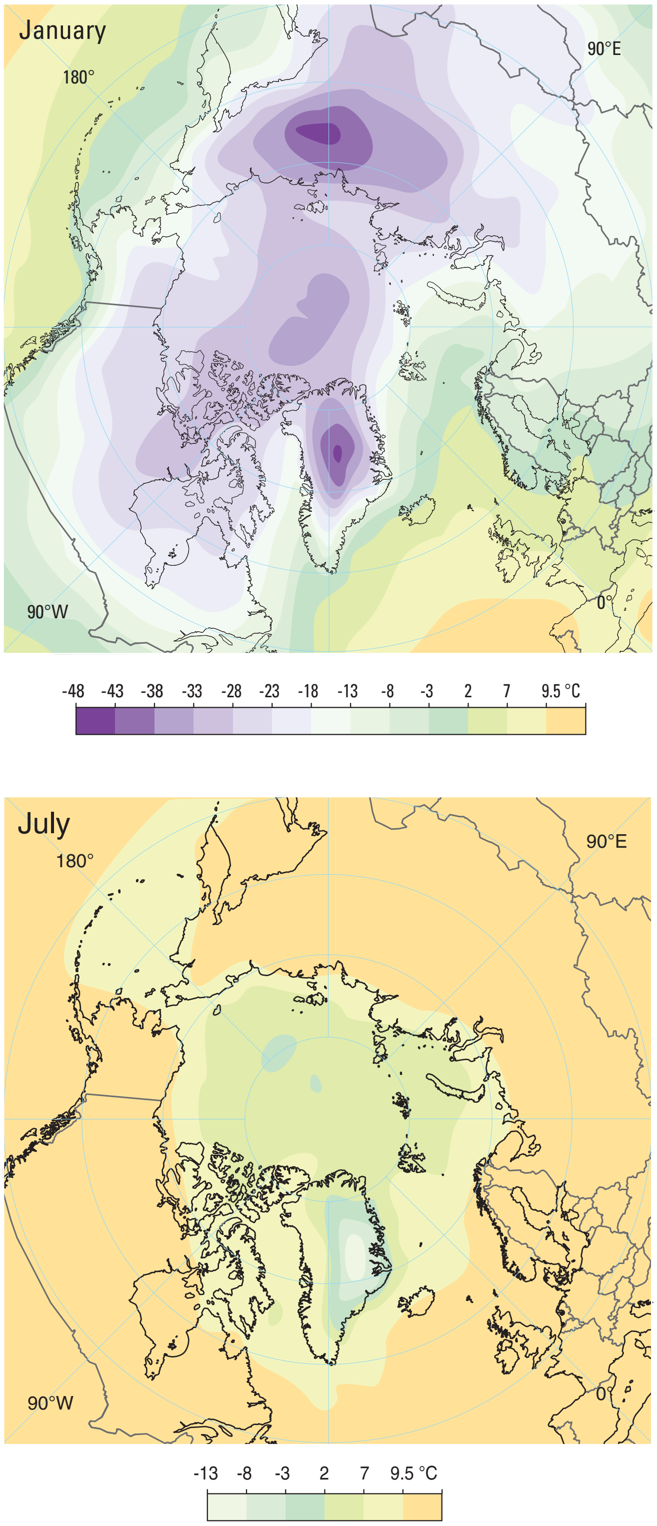

Figure 2·5. Mean January and July surface air temperatures (°C) in the Arctic (Parkinson *et al.* 1987).

apparent if one compares temperatures among stations at similar latitudes. The average January temperature of a station in the Canadian Arctic Archipelago is approximately 20°C lower than the January temperature of a station at the same latitude on Svalbard. The warming effect of the moving depressions extends as far as the northeastern parts of the Barents Sea. During the summer season, temperature variations along the latitudes are much reduced, due to the moderating effect of the sun's heat.

2.3.3.2. **Ocean temperature**

As in the atmosphere, there is both annual and interannual variability in ocean temperature. This is most pronounced in the warmer water masses. Variability in cold Arctic waters is small, but important. In the North Atlantic, the ocean appears to alternate between warm and cold states. The length of these states may vary, but fluctuations with periods of 3-5 years are most frequent. The varying temperature condition in the western North Atlantic is opposite to that in the eastern North Atlantic. This means that when the Barents Sea is in a warm state, the coast of Newfoundland is in a cold state (Sundby pers. comm.). This feature is also found in the distribution of ice. When there are heavy sea ice conditions in the northeast Atlantic, there is little ice in the Labrador Sea, and vice versa (Gloersen *et al.* 1992). There is also large variability in ice distribution in the Bering Sea, but at present, there is no evidence that this is linked to the variability in the Atlantic.

The temperature state of the ocean appears to be closely linked to atmospheric circulation, with a positive feedback mechanism existing between the atmospheric and oceanic circulations. It appears that high atmospheric pressure is associated with low temperatures in the ocean while low pressure is related to a warmer ocean. Changes in ocean climate influence transport mechanisms and ice cover. In warm years, there is an increased transport of warm water masses to the Arctic, resulting in decreased ice cover. In cold years, transport of warm water to the Arctic is reduced and sea-ice coverage is greater (Ikeda 1990a, 1990b, Aadlandsvik and Loeng 1991).

2.3.3.3. **Precipitation**

The total annual precipitation in the Arctic is generally less than 500 mm and typically between 200 and 400 mm (Loshchicov 1965) (Figure 2·6). Along the Arctic coast, the precipitation is higher, and over the central Polar Basin it is lower. Cold air contains less moisture, therefore, although the frequency of precipitation may be high, the overall inten-

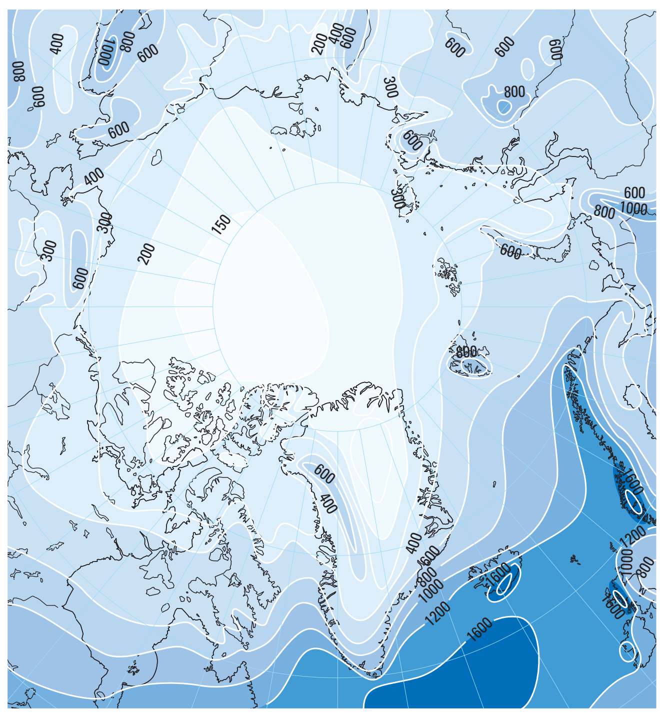

Figure 2·6. Distribution of precipitation (mm/y) in the Arctic (AARI 1985).

sity is low. This explains why the total accumulation of snow is relatively low in winter over much of the Arctic.

The spatial precipitation pattern in the Arctic can be explained in terms of the effects of elevation changes and proximity to maritime sources of moisture. Precipitation levels decline with increasing distance inland from the oceans, and in general, levels decrease in a west-east direction across the continents in the direction of movement of most low-pressure systems.

The lowest precipitation levels on land are approximately 140 mm/y, occurring in eastern Siberia, northern Canada and Greenland. In general, total precipitation increases to above 600 mm/y from these areas toward the Atlantic and Pacific Oceans (Sugden 1982).

Maritime areas in the subarctic have much higher precipitation. In southern Iceland, the annual precipitation ranges from below 800 mm to over 3000 mm, and on mountains and glaciers it can exceed 4000 mm (Einarsson 1984). The precipitation decreases toward the east and north, with 700-2000 mm/y at Bodø to less than 400 mm/y at Murmansk, Russia and Longyearbyen, Svalbard (EEA 1996).

2.3.3.4. Cloud cover

An important climatic feature of the Arctic is the presence of persistent and extensive stratus cloud cover over the polar oceans. The cloud cover occurs in well-defined layers separated by clear interstices. The structure of the clouds is related to the large-scale transport of relatively mild, humid air into the Arctic Basin, the boundary layer turbulence, and the optical properties of the liquid water droplets. Clouds are formed largely during the summer season; the cloud cover varies from a summer amount of 70-90% to 40-60% in winter (Landsberg 1970).

During periods of cold air outbreaks from the Arctic Basin, clouds are formed by cooling of the boundary layer air previously at higher temperatures because of the relatively warm sea surface underneath. Characteristic cloud strips following the wind direction cover large areas of the open sea.

2.3.3.5. Fog

A characteristic feature of Arctic weather is fog. Parts of the Arctic are extremely foggy due to the juxtaposition of cold air overlying warmer ocean waters in some areas and warm air overlying cold ice in others. In some areas, it is typical to have more than 100 days per year with fog (SCOR 1979). In summer, the ice retreats northward, exposing open water, and warm air moves in over the ice and cold water. Sublimating ice and condensing water form thick fog fields that envelop the marginal ice zones, with peaks in relative humidity over water in August. In winter 'sea smoke' or steam fog forms over open water leads in the pack ice (SCOR 1979).

2.3.3.6. Wind

Winds are particularly important for the Arctic surface environment, as they can greatly augment the chilling effect of low temperatures. The generally open landscape of the Arctic region means that winds are not greatly slowed by friction at the ground level (Sugden 1982). Wind is an important factor in snow distribution, causing scouring in exposed areas and deposition in sheltered locations (Killingtveit and Sand 1991).

In the marine environment, wind affects sea surface stability and increases mixing in the water column. It also influences ice drift (Vinje 1976) and the formation of polynyas. Winds, or more precisely differences in air pressure which cause winds, are often closely related to ocean circulation as discussed by Ikeda (1990b) and Aadlandsvik and Loeng (1991).

Surface winds are greatly affected by the presence of temperature inversions. In Greenland, katabatic winds are formed as air in the dense, cold inversion layer flows down the slopes of the ice sheet toward the coast under the influence of gravity. These winds are especially well developed in winter when the air comes into contact with the ice surface and is chilled. With the exception of these parts of Greenland, wind speeds are generally slowed by temperature inversions as the air is effectively isolated from faster-moving air currents above (Sugden 1982).

Two dominant air currents in the Arctic are associated with cold air flowing in winter from the high-pressure zone over northern Siberia to the Pacific, and air flowing northwest from the high-pressure area over the Canadian Arctic toward the low pressure over the Atlantic. These winds result in very severe climatic conditions in the Arctic, and in Canada, these conditions persist into the early summer (Sugden 1982).

2.4. Physical/geographical description of the terrestrial Arctic

2.4.1. General geographical description

The vast Arctic terrestrial landscape, covering an area of approximately 13.4×10^6 km^2 within the AMAP boundary, is very diverse (Figure 2·7), with large tracks of land covered by glacial ice. Glaciers are large masses of ice that flow under their own weight. They form where the mean winter snowfall exceeds the mean summer melting. Melting, refreezing and pressure gradually transform the snow into ice.

Greenland, often described as the largest island in the world, is actually comprised of numerous mountainous islands almost entirely covered with a permanent ice cap up to 3000 m thick (Stonehouse 1989, Bjerregaard 1995). It spans 24 degrees of latitude (2670 km), is 1200 km across at its widest point, and covers an area of some 2 186 000 km^2. The main tracts of ice-free land are in the southwest, the north (Peary Land) and the northeast (north of Scoresbysund). Along the Greenland coast, outlet glaciers flow from the ice sheet to the sea. Glaciers terminating in the sea periodically break off, or calve, forming icebergs.

Iceland is located south of the Arctic Circle (66°32'N). This mountainous and volcanically active island lies on the mid-Atlantic ridge. Its average height is approximately 500 meters above sea level. One quarter of the country is less than 200 m above sea level. It has an area of 103 000 km^2, with 11% of its surface covered by glaciers and more than 50% of its land surface unvegetated (Stonehouse 1989, Ministry for the Environment 1992).

The Faeroe Islands, with a total area of 1399 km^2, are located 430 km southeast of Iceland. The terrain is mountainous with an average elevation of 300 m.

Svalbard and Franz Josef Land are Arctic archipelagos of 63 000 and 10 000 km^2, respectively. These mountainous islands, and others lying to the north of Eurasia, are about 90% covered by ice.

The Fennoscandian Arctic area covers roughly 300 000 km^2, but most of this area is subarctic due to the warming influence of the Gulf Stream extension (Stonehouse 1989, Encyclopedia Britannica 1990).

The Kola Peninsula (ca. 145 000 km^2) on the Russian mainland is also subarctic and contains many lakes. Permafrost is absent, except for sporadic occurrences at the tip of

Figure 2·7. Topography and bathymetry of the Arctic (based on the ETOPO5 data set, NOAA 1988).

the peninsula, and the coasts are ice-free (Ives 1974, Luzin *et al.* 1994). The Russian Arctic west of the Ural Mountains shows much variation in landscape, but large areas consist of flat, poorly drained lowlands with marshes and bogs. The Siberian coast is generally flat and includes the deltas of many large, north-flowing rivers. Ice-covered mountains are characteristic of the Russian peninsulas of Taimyr and Chukotka. In eastern Siberia, there are several mountain ranges (e.g., Verkhoyansk, Chersky and Momsky) with peaks reaching heights of over 2500 m. The entire area of Arctic Russia within the AMAP boundary is approximately 5.5×10^6 km^2.

The numerous islands of the Russian Arctic cover an area of 135 500 km^2. The largest of these is Novaya Zemlya, an archipelago with two main islands. The northern island is mountainous, with about half of the 48 000 km^2 area covered by glaciers and a small ice cap. The southern island is smaller (33 000 km^2), largely ice-free, and characterized by large coastal plains, especially in the southern parts.

Alaska's Arctic, according to the AMAP definition, extends over an area of 1.4×10^6 km^2, and is dominated by rugged mountain ranges that stretch across the state in the south and north, reaching a maximum height of 6194 m at Mount McKinley. Extensive glaciers are found in the south central and southeastern mountains. These ranges give way to foothills and low-lying coastal tundra plains in the southwest and along the northern coast of Alaska. Extending westward into the Pacific Ocean beyond the Alaska Peninsula are the volcanic Aleutian Islands (Stonehouse 1989).

The Canadian Arctic landscape covers an area of approximately 4×10^6 km^2, comprised of the northern Canadian mainland in the south and the Arctic archipelago to the north. At the most western boundary of the mainland is the Yukon Plateau, consisting of rolling uplands with valleys and isolated mountains. Southwest of this plateau are the Coast Mountains with extensive glaciers. To the northeast are the Mackenzie Mountains. These mountain ranges give way to the Interior Lowlands, comprised of plateaus ranging in height from 1200 m in the west to 150 m in the east. This region, which is transected by the Mackenzie River, is characterized by extensive wetlands. The large Great Bear and Great Slave Lakes extend from the Interior Lowlands eastward into the Canadian Shield. The Shield extends to the east coast and contains numerous lakes and the vast expanse of Hudson Bay (National Wetlands Working Group 1988, Prowse 1990).

The Canadian Arctic Archipelago extends far to the north of the mainland. Flat to rolling terrain is characteristic of the High Arctic islands in the western and central archipelago (e.g., Banks, Melville, Victoria, Bathurst and Prince of Wales Islands). The northeastern islands (Baffin, Devon, Ellesmere and Axel Heiberg) contain rugged, ice-capped mountains up to 2000 m in height (Prowse 1990, Woo and Gregor 1992, Sly 1995).

Figure 2·8. Geologic and physiographic regions of the Arctic (after Linell and Tedrow 1981, by permission of Oxford University Press).

2.4.2. Geology and physiography

The major physiographic regions and bedrock geology of the Arctic are presented in Figures 2·8 and 2·9, respectively.

Greenland, and a vast region of the Canadian Arctic, from the Atlantic Ocean in the east to Great Bear Lake and Great Slave Lake in the west, is underlain by the Canadian Shield. This Precambrian, crystalline rock mass is exposed in some areas and covered by glacial deposits and thin soil in others. The Canadian Shield extends northward to include Baffin Island. The remaining islands in the Canadian Arctic Archipelago are primarily made up of Paleozoic and Mesozoic sedimentary rocks. Along the southwest coast of Hudson Bay are the Hudson Lowlands, comprised mainly of Lower Paleozoic rock and covered by Quaternary sediments. To the west of the Shield are the Interior Plains made up of Devonian and Cretaceous sedimentary formations. The North American Cordillera, a wide belt of high mountains and plateaus of Paleozoic, sedimentary origin, extend along western Canada and Alaska. In Alaska, these mountains merge to the north with the Arctic Foothills, which descend still farther north into a coastal plain (Linell and Tedrow 1981, Prowse 1990, Natural Resources Canada 1994).

Iceland has been created by volcanic activity along the mid-Atlantic ridge during the last 20 million years. New volcanic rock is constantly being added and about one-tenth of Iceland is covered by lava deposited since the last ice age (Einarsson 1980). The Aleutian Islands to the west of Alaska are also volcanic.

Northern Fennoscandia and the Kola Peninsula are comprised of ancient, crystalline rocks forming the Baltic Shield. East of this region, from the White Sea to the Ural Mountains, lies the East European Plain, made up of sedimentary rock covered by a deep layer of glacial drift. The Ural Mountain complex, which includes Novaya Zemlya, is a region of folded Paleozoic bedrock, covered thinly with glacial deposits. The other Russian Arctic islands are also primarily formed by sedimentary formations of the Paleozoic Era. The West Siberian Lowland, comprised of till-covered sedimentary rocks, extends from the Urals to the Yenisey River. From here, eastward to the Lena River, is the Central Siberian Plateau. This till-covered region is underlain by the

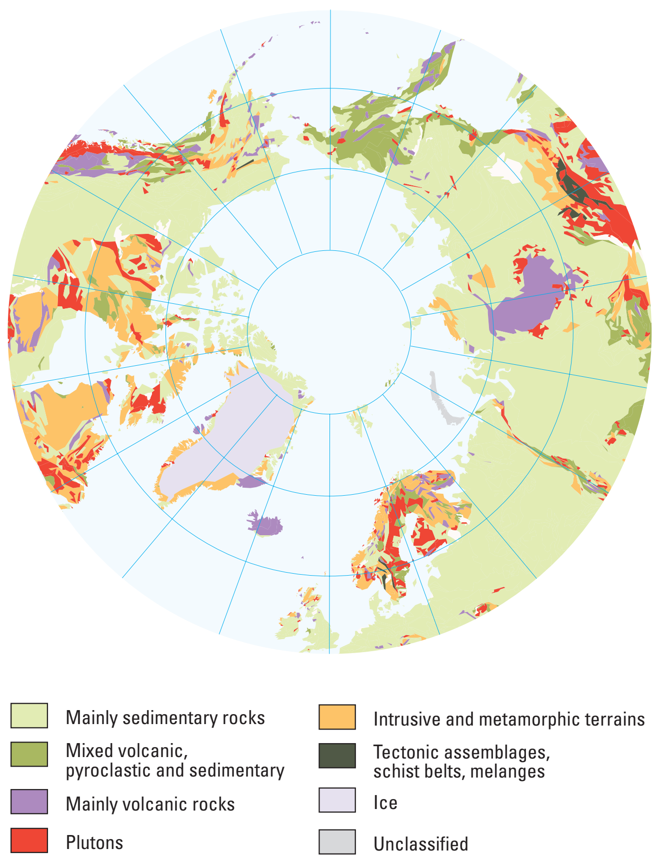

Figure 2·9. Bedrock geology of the Arctic (Geological Survey of Canada 1995).

Anabar Shield and peripheral sedimentary rocks. To the north, the Taimyr Peninsula contains a folded mountain complex of sedimentary rocks, overlain by shallow soils. The region east of the Lena River is similarly comprised of folded sedimentary mountains, with some volcanic rocks. Glacial drift is discontinuous in this region (Linell and Tedrow 1981). Low plateaus and plains are characteristic of the region through which the Lena River passes and of the

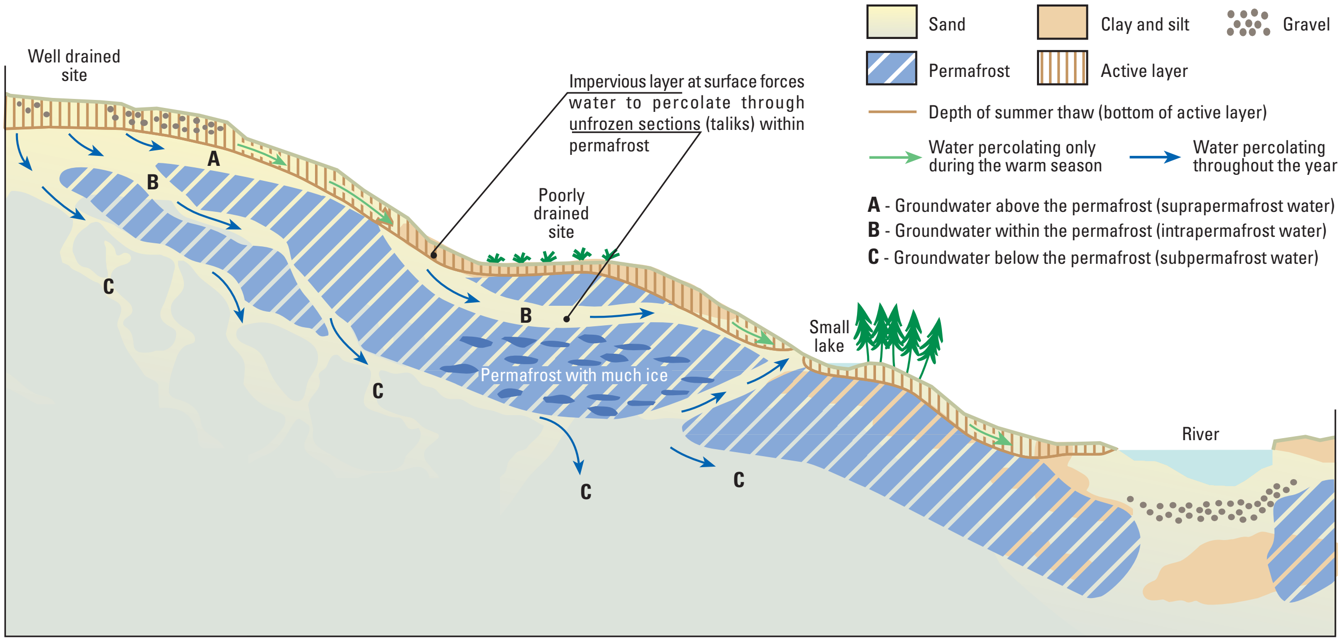

Figure 2·10. Occurrence of groundwater in permafrost areas (after Mackay and Løken 1974, Linell and Tedrow 1981).

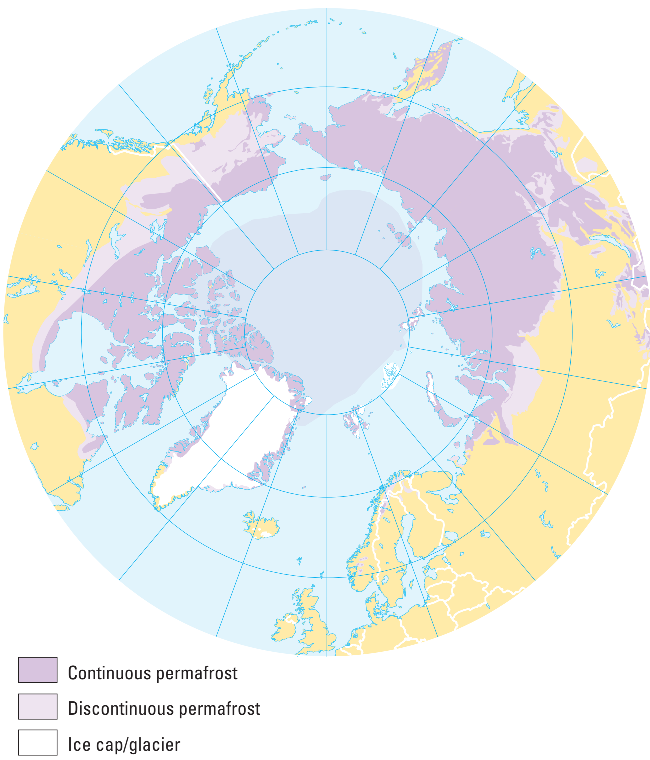

Figure 2·11. Circumpolar permafrost distribution (CAFF 1996).

northern margin of Siberia from the Taimyr Peninsula to the Kolyma River (Sachs and Strelkov 1961 in Linell and Tedrow 1981).

2.4.3. Permafrost and soils

Permafrost, or perennially frozen ground, is defined as material that stays at or below 0°C for at least two consecutive summers (Woo and Gregor 1992). It may consist of soil, bedrock or organic matter. Spaces within the ground material may be filled with ice in the form of ice lenses, veins, layers and wedges. When very little or no ice is contained in the frozen substrate, this is referred to as dry permafrost (Figure 2·10) (Linell and Tedrow 1981). Permafrost may reach depths of 600-1000 m in the coldest areas of the Arctic (Stonehouse 1989).

The distribution of permafrost is broadly determined by climate, particularly air temperature and the resultant energy balance between the air and the ground. Several secondary factors which affect permafrost occurrence include elevation, composition and color of the ground surface, ground aspect, soil moisture, and extent and type of plant cover. Permafrost is generally not found under large bodies of water greater than three meters deep, the maximum depth to which winter ice develops. The insulating effects of glaciers and extensive snow cover also reduce permafrost development (Ives 1974). Figure 2·11 shows distribution of continuous and discontinuous permafrost north of 50°N. Perennially frozen ground occurs throughout the Arctic and extends into the forested regions to the south. Along the northern coastlines, frozen grounds meet the sea, with permafrost extending under some shelf seas.

Permafrost influences soil development in the north. In general, Arctic soils are either poorly drained and underlain by solid, ice-rich permafrost, or well drained and situated over dry permafrost. Poorly drained soils are found in 85-90% of the Low Arctic and in the few wet meadows of the High Arctic. Well-drained soils are common in the extensive, sparsely vegetated areas of the High Arctic, and are scattered throughout the Low Arctic in areas where water can escape, such as on steep slopes and beach ridges. Oxidation processes in these drier soils result in lower organic matter content compared to wetter soils (Rieger 1974, Everett *et al.* 1981).

During the summer, the upper layer of soil in the Arctic thaws and is termed the active layer. Its depth varies according to temperature, ground material, soil moisture content and plant cover, ranging from as little as several centimeters in far northern wet meadows to as deep as a few meters in warmer, more southern, dry areas with coarse-grained soils (Ives 1974) (Figure 2·10). Soil-forming processes are largely restricted to the active layer, which is unstable due to frost action during repeated freezing and thawing. Frost action results in characteristic surface features, such as frost scars, stone circles, mud circles, solifluction lobes and stone stripes (Rieger 1974, Stonehouse 1989).

2.5. Arctic freshwater environments

2.5.1. Rainfall and snow

The Arctic is characterized by short summers and therefore short periods with rainfall. The remaining precipitation falls as snow, which accumulates as snowpack over the winter. Snowpack duration, away from the moderating influences of coastal climates, ranges from about 180 days to more than 260 days (Grigoriev and Sokolov 1994).

High levels of solar radiation reaching northern latitudes in spring result in rapid snowmelt. Spring runoff comprises 80-90% of the yearly total, and lasts only two to three weeks (Linell and Tedrow 1981, Rydén 1981, Marsh 1990). Infiltration of this flush of water into the ground is constrained by the permafrost. Thus, spring meltwater may flow over land and enter rivers, or accumulate into the many muskegs, ponds and lakes characteristic of low lying tundra areas (van Everdingen 1990). Summer sources of water include late or perennial snow patches, glaciers, rain, melting of permafrost, and groundwater discharge (Rydén 1981, van Everdingen 1990).

2.5.2. Groundwater

Groundwater levels and distribution within the Arctic are greatly influenced by permafrost. Permafrost affects the amount of physical space in which groundwater can be held and the movement of water within drainage systems. There are three general types of groundwater: suprapermafrost, intrapermafrost and subpermafrost (Figure 2·10). Suprapermafrost water lies above the relatively impermeable permafrost table in the active layer during summer, and year-round under lakes and rivers that do not freeze. Intrapermafrost water resides in unfrozen sections within the permafrost, such as tunnels called 'taliks', located under alluvial flood plains and under drained or shallow lakes and swamps. Subpermafrost water is located beneath the permafrost table and its depth below the surface depends on the thickness of the permafrost. In this latter case, the permafrost acts as a relatively impermeable upper barrier. These three types of aquifers, which may be located in bedrock or in unconsolidated deposits, may interconnect with each other or with surface water (Mackay and Løken 1974, van Everdingen 1990).

Generally low levels of annual precipitation in the Arctic restrict the recharge of groundwater. In addition, infiltration of water to aquifers is restricted by permafrost year-round and by the frozen active layer for up to ten months of the year. Frozen substrate does not entirely prevent water from seeping through to aquifers, but slows the rate of infiltration by one or more orders of magnitude compared to unfrozen ground (van Everdingen 1990).

The degree of groundwater recharge is influenced by the material comprising the substrate. Recharge is greatest in regions with coarse-grained, unconsolidated material and areas with exposed bedrock containing channels or fractures which allow passage of water. Infiltration, and therefore recharge, is least in areas covered by fine-grained deposits such as silt and clay (van Everdingen 1990).

Groundwater is discharged via springs, base flow in streams, and icings. These discharges can be fed by supra-, intra- or subpermafrost water. Perennial springs are generally fed by subpermafrost aquifers and less commonly by intrapermafrost water. Icings (also known as aufeis or naleds) are comprised of groundwater that freezes when it reaches the streambed during winter when base flow freezes. When fed by suprapermafrost water, icings generally stop growing before the end of winter. Icings formed by discharge from intra- or subpermafrost groundwater continue to build until temperatures climb above 0°C in spring. In cases of large icings, spring melt and runoff can result in significant redistribution of groundwater (van Everdingen 1990).

Groundwater is quite extensive in the Arctic. For example, approximately two-thirds of the Yukon in the Canadian Arctic is underlain by aquifers (Hardisty *et al.* 1991). The largest groundwater aquifers in Iceland have been mapped in Elíasson (1994). These are generally found in highly permeable lava. Groundwater represents an important source of water in some Arctic countries.

2.5.3. Wetlands

Wetlands and saturated soils are characteristic features of the Arctic since moisture received from rain and snowmelt is retained in the active layer above the permafrost barrier. Due to the higher levels of precipitation received at lower latitudes, wetlands are more common in the Low Arctic than the High Arctic. In general, wetlands are sparsely distributed throughout the Arctic, but tend to have significant local concentrations.

Arctic wetlands are distinct due to the unique climatic conditions under which they were formed. Permafrost underlies almost all Arctic wetlands. A number of different forms of wetlands exist in the Arctic and are described below (National Wetlands Working Group 1988).

2.5.3.1. Lowland polygon bogs and fens

Two types of lowland polygons are found in the Arctic, those with a low center and those with a high center (Figure 2·12). When soil temperatures fall below –15°C in winter, the ice within the soil contracts forming cracks and eventually ice wedges. Low-center polygons are bowl-shaped with the

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Figure 2·12. Low and high-center polygons.

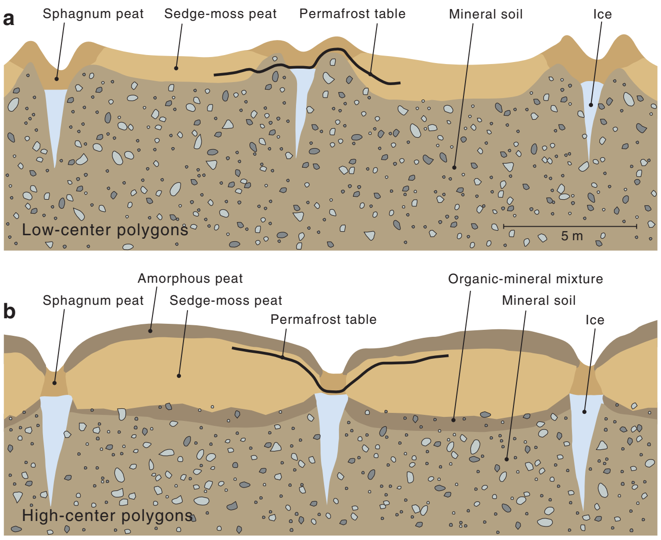

Figure 2·13. Low-center and high-center polygon development (after National Wetlands Working Group 1988).

edges pushed up by surrounding ice wedges (Figure 2·13a). The depressed centers of these polygons fill with water, creating small ponds. The peat layer in low-center polygons is thin. Over time, the peat builds up, gradually filling the depression and forming a raised or high-center polygon. High-center polygons, therefore, represent a more advanced stage of lowland polygon development (Figure 2·13b). These polygons vary in size, but are commonly about 8 m in diameter (National Wetlands Working Group 1988).

Bogs and fens are both referred to as mires, i.e., areas with appreciable peat accumulation. When the peat is fairly acid (pH 3.0-5.0) the wetland is called a bog. The peat in fens is more neutral due to regular flooding with base-enriched waters (Moore 1981).

2.5.3.2. **Peat mound bogs**

Peat mound bogs are simply peat-covered mounds, 1-5 m in diameter, that rise about 1 m above ground (Figure 2·14). As peat builds up in an area of a wetland, the insulating effect causes thinning of the active layer beneath, and growth of segregated ice under and within the peat, thereby forming a dome.

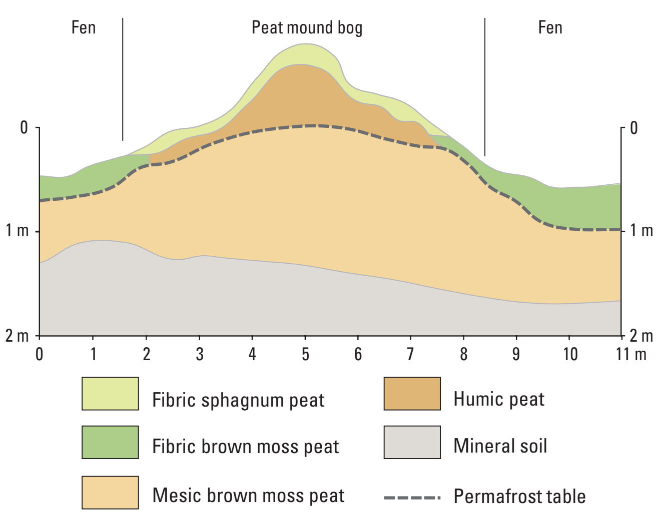

Figure 2·14. Cross-section of a peat mound bog (after National Wetlands Working Group 1988).

2.5.3.3. **Snowpatch fens**

In the High Arctic, snow patches form below the brows of hills on the lee side. With accumulations of up to 2 m, melting of this snow can provide water to the slopes below throughout the summer. If the slope of the hill is gradual, this meltwater will flow in sheets, creating wetlands along its course.

2.5.3.4. **Tundra pool shallow waters**

Dotted throughout the landscape of the northern Low Arctic and the High Arctic are small ponds, usually less than 1 ha in area and less than 0.5 m deep. The edges of these pools tend to be peaty.

2.5.3.5. **Floodplain marshes**

Floodplain marshes are located in active floodplains alongside river channels. These marshes tend to have high water levels during spring melt and low levels in the fall. Water levels in floodplain marshes located in estuaries and deltas near the sea are additionally affected by the tide. Due to high sedimentation loads in these marshes, the build-up of organic matter is limited.

2.5.3.6. **Floodplain swamps**

Similar to floodplain marshes, floodplain swamps are found in river deltas, but have open drainage due to an unrestricted connection to the river channel. Water levels in these swamps are highest in spring and gradually decline until the fall. Again, due to heavy sedimentation, little organic matter accumulates in the soils of these swamps.

2.5.3.7. **Wetland occurrence**

In the Canadian Arctic, approximately 3-5% of the land area is covered by wetlands. Areas of high occurrence (between 20 and 75% coverage) include the Yukon coastal plain, the Mackenzie Delta, and parts of the Arctic islands (National Wetlands Working Group 1988).

Mires are uncommon in Greenland, and in Alaska they are restricted to the northern mountains. In Norway, only 0.9% of the Arctic region is classified as wetland and bog area. Sweden reports 21% of its Arctic land area as mire (CAFF 1994). In Finland, approximately half of the original wetland area has been disturbed for forestry, leaving about 15% of the country covered by wetlands (Keltikangas *et al.* 1986).

In the Russian Arctic, large areas are dominated by bogs and marshes including the Kola Peninsula, West Siberia, the Yamal Peninsula and the lowlands of the Yana, Indigirka, and Kolyma River basins (Plancenter Ltd. 1991, Bliss and Matveyeva 1992).

2.5.4. **Rivers**

Two main types of rivers occur in the Arctic, those that have headwaters within the Arctic and those with headwaters farther south (Woo 1992). Most of the large Arctic rivers begin their flow south of the Arctic, including the major rivers of Siberia (Ob, Yenisey, and Lena) and the Mackenzie River in Canada (Mackay and Løken 1974). The mean annual runoff to the Arctic Ocean from the largest Arctic rivers is shown in Figure 2·15.

Flow in Arctic rivers is largely influenced by rain, snowmelt and ice melt because of the drainage barrier of the per-

Figure 2·15. Arctic Ocean watershed and catchment areas of some rivers and annual runoff (km^3/y) of major rivers to the Arctic Ocean.

mafrost and the limited water storage capacity of the thin active layer (Newbury 1974 in Woo 1992). River flow is also affected by lake/reservoir storage and by groundwater input (e.g., the Lena River in winter) (Gordeev and Sidorov 1993). Most Arctic rivers exhibit an Arctic nival regime, meaning that their main flow takes place during the period of spring melt. When the melt is completed, water levels in the river drop to base flow only. Some northern rivers display a proglacial regime, flowing throughout the summer due to input from glacial melt. Rivers flowing through wetlands follow a wetland or muskeg regime, with the main flow occurring with the spring snowmelt when the ground is still frozen (Woo 1992).

In some areas, such as the Canadian Cordillera, rivers tend to be erosive, undercutting their banks and creating large, braided channels. Therefore, these rivers have large sediment loads and leave behind deposits of this sediment along their course as braided channels and eventually as large deltas (Stonehouse 1989), and contribute to bottom sediments in lakes and reservoirs. Other parts of the Arctic, such as the Precambrian shield, lack the surficial deposits necessary to provide a source of river sediment.

The break-up of ice in Arctic rivers begins at the river edge as melt water flows in from adjacent river banks and slopes. Increased flow onto the surface breaks the ice cover into pieces. Leads develop across the river at locations of incoming streams. Intermittent and slow flow of the river begins as the ice edge gradually loosens from the riverbank. Ice jams form at narrow and shallow areas of the river, eventually giving way under the pressure of water coming in from tributaries and with continued melting and ice abrasion. When the ice jams break up there is an initial surge of water followed by a drop in water level, which leaves pieces of ice stranded along the river bank. Mean break-up dates of Arctic rivers are shown in Figure 2·16 (Mackay and Løken 1974).

Arctic rivers tend to remain cool throughout the short summer season due to the addition of cold melt waters. Small, shallow streams may be quickly warmed by solar radiation to 10-20°C, but these warm waters have little effect on the low temperatures of larger rivers systems.

Freeze-up in Arctic rivers begins with the drop in temperatures in the fall. The progression of freeze-up in rivers is similar to that of lakes (refer to section 2.5.5). In addition to the wind and wave action which causes vertical mixing of lake and river water, turbulent flow in rivers can have the same effect, thereby creating a thicker surface cooling layer in the autumn. Mean dates for river freeze-up in the Arctic are shown in Figure 2·17 (Mackay and Løken 1974).

Figure 2·16. Mean dates of river break-up in the Arctic; month number in Roman numerals (after Mackay and Løken 1974).

Figure 2·17. Mean dates of river freeze-up in the Arctic (after Mackay and Løken 1974).

2.5.5. Lakes

The eastern and central North American and western Eurasian Arctic regions were covered with glaciers during the Pleistocene epoch. Glaciation of eastern Asia was less extensive. These large glaciers carved out the land as they moved over it, gouging out topsoil and broken rock. The many depressions left behind filled with water when the glaciers melted, forming lakes.

Following the retreat of the continental glaciers, the land which had been pushed downward by the weight of the ice, began to rise, a process called isostatic rebound. This rebound is still occurring today, and though it is at a much slower rate than when it began, eastern Hudson Bay, for example, continues to rise at a rate of one meter per century. New lakes are thus still being formed as gouged land rises up out of the sea. Lakes closer to sea level are often younger than those at higher elevations (Welch and Legault 1986).

Other types of natural lakes exist in the Arctic. Kettle lakes result from the thaw of buried glacier ice (Washburn 1979). Thermokarst lakes are formed in depressions that result from permafrost melting. Ice-dammed lakes are more common in the Arctic than elsewhere and in Greenland all the larger lakes are of this type. These lakes are prone to periodic draining (Mackay and Løken 1974).

There are innumerable small lakes in the Arctic. In the Province of Murmansk in Russia, there are over 100 000 lakes, the largest of which is Lake Imandra with an area of 812 km^2 and a maximum depth of 67 m (NEFCO 1995). Iceland, Sweden and Finland have approximately 2.7, 5.2 and 5.8%, respectively, of their land area occupied by lakes. Only about 0.5% of Alaska is covered by freshwater (CAFF 1994). The Canadian Arctic contains many lakes, including the large Great Bear (31 326 km^2) and Great Slave (28 568 km^2) Lakes located on the mainland (Mackay and Løken 1974). In the central Canadian Arctic, 20% of the land surface is covered by water.

There are also artificial lakes or reservoirs within the Arctic that have been created along Arctic rivers for the purpose of hydroelectric power generation. In Canada and Russia, some of these reservoirs are quite large, for example, those for the James Bay project in Canada, and the Kransnoyarskoye Reservoir on the Yenisey River in Siberia.

The time at which Arctic lakes become ice-free is largely dependent on June temperature and windspeed (Welch *et al.* l987). Ice thaw begins when meltwater from the surrounding watershed flows out onto the lake ice and enters cracks and holes in its surface. Shore leads then develop along the lake's perimeter, eventually breaking the connection of ice with the edges and bottom of the lake. The water on the ice surface gradually melts through the free-floating ice. A combination of melting temperatures and weather activity continue the thawing process (Mackay and Løken 1974). Ice-out in Arctic lakes ranges from early July in the south to mid-August in the High Arctic, with some lakes at very high latitudes remaining partly or entirely ice-covered throughout the year (Rust and Coakley 1970, Schindler *et al.* 1974, Welch *et al.* 1987).

The period of peak incoming solar radiation has already passed by the time the ice is off Arctic lakes, and much of the radiation received prior to this time is used to melt the ice (Schindler *et al.* 1974, Welch *et al.* 1987). Therefore, water in Arctic lakes has little opportunity for warming. Freshwater is densest at 4°C and sinks below water that is warmer or colder than this temperature, thereby producing stratification. Weak thermal stratification is found in Low Arctic lakes where surface water has greater opportunity to warm up, compared to the High Arctic, where lakes tend to be vertically mixed (Mackay and Løken 1974, Welch *et al.* 1987). Small, shallow lakes throughout the Arctic, which lose their ice quickly, may become quite warm (>10°C). Such lakes do not stratify due to surface wind mixing. Maximum surface water temperatures range from about 15°C in small lakes near the treeline, to 4-6°C in ice-free lakes north of 75°N (Welch, unpubl.).

With the onset of cooler weather and fall storms in mid-August, Arctic lakes lose heat rapidly and mix completely throughout their depth. Because the lakes are unprotected by trees and high winds are common, Arctic lakes tend to cool well below the temperature of maximum density (4°C), with the entire water column often reaching 0°C before there is significant ice formation at the surface. Freeze-up occurs between the first week in September and mid-October, depending upon the latitude and size of the lake. Ice thickness increases linearly until April or May, reaching depths between 1.5 and 2.5 m (first year ice). Ponds with depths less than maximum ice thickness (typically 2.0-2.2 m) freeze to the bottom. Thus, Arctic lakes are partly frozen for 9-12 months of the year (Welch *et al.* 1987, Welch 1991).

2.5.6. Estuaries

Estuaries are semi-enclosed, coastal bodies of water, connected to the open ocean, and containing seawater diluted by freshwater from land drainage (Lauff 1967, Pritchard 1967). In a broad sense, river deltas, fjords and bays may be considered as estuaries, and they are important parts of the coastal zone. With the exception of Norwegian and Icelandic fjords, they are influenced by ice cover for most of the year. Fast ice often starts to develop in October, and remains in place until break-up in June (Macdonald *et al.* 1995, Pfirman *et al.* 1995). Thus, for most of the year in the Arctic, river runoff enters the ocean under an ice cover.

The coastal zone is the interface between the terrestrial/ freshwater processes and the oceanic processes. Deltas and estuaries play an important role in sedimentation in freshwater systems and strongly influence contaminant transport to oceans. There is a significant difference between summer and winter regimes of estuarine zones. The summer regime is characterized by maximum river discharge, intensive chemical and biological processes, and high sedimentation rates. During winter, the freshwater runoff and fluxes of suspended and dissolved substances are low.

2.6. Arctic marine environment

2.6.1. Geographical area and bathymetry

The circumpolar Arctic region is dominated by the Arctic Basin. The Arctic marine area within the AMAP boundary includes the Arctic Ocean, the adjacent shelf seas (Beaufort, Chukchi, East Siberian, Laptev, Kara, and Barents Seas), the Nordic Seas (Greenland, Norwegian, and Iceland Seas), the Labrador Sea, Baffin Bay, Hudson Bay, the Canadian Arctic Archipelago and the Bering Sea. This represents an area of approximately 20×10^6 km^2. The connection with the shallow Bering Sea (and the Pacific Ocean) occurs through the narrow Bering Strait, while the main connection with the Atlantic Ocean is via the deep Fram Strait and the Nordic Seas.

The Arctic Ocean is divided into two deep basins, the Eurasian and the Canadian, by the transpolar Lomonosov Ridge (Figure 2·7). The Canadian Basin is transected into the Makarov and Canada Basins by a ridge in the north, the Alpha Cordillera, and reaches depths of more than 3500 m. The continental shelf is narrow off most of Arctic North America, extending only 50-100 km from the coast, except in the southeastern Beaufort Sea, where it reaches some 150 km offshore (French and Slaymaker 1993).

The Eurasian Basin is smaller but deeper than the Canadian Basin, reaching depths of 4000 m. It is bisected by the narrow Nansen Cordillera into the Amundsen and Nansen Basins. North of Siberia, the continental shelf is vast and

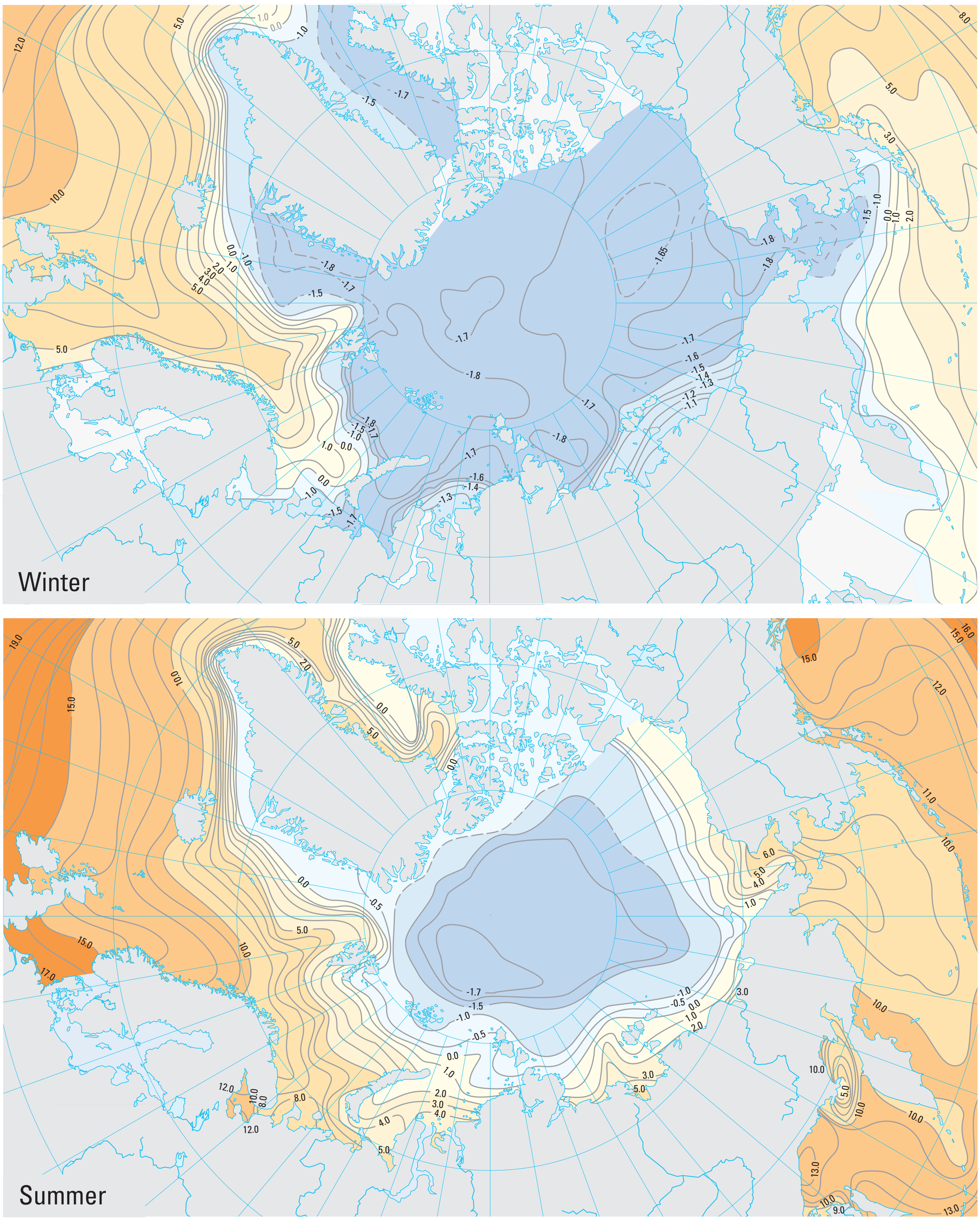

Figure 2·18. Winter and summer surface water temperatures (°C) in the Arctic Ocean and adjacent seas (USSR Ministry of Defense 1980).

extends up to 900 km from the coast (Sugden 1982, Macdonald and Bewers 1996).

2.6.2. Hydrographic conditions in the Arctic

Ocean temperatures within the AMAP area show large variation depending on latitude and the influence of warm Atlantic and Pacific water. Figure 2·18 shows surface ocean temperatures in the Arctic during winter and summer. In the Arctic Ocean, there are only small variations in temperature between winter and summer. Due to ice coverage, the temperature in this area is close to the freezing point year-round. In the shelf areas, surface water temperatures in winter are close to freezing (just below –1°C), while during summer they may increase to 4-5°C due to heating from the sun. In areas influenced by Atlantic and Pacific water, there may be greater seasonal variability, for example in the northeast Atlantic and parts of the Bering Sea. In these areas the temperature remains higher than 0°C throughout the year (USSR Ministry of Defense 1980).

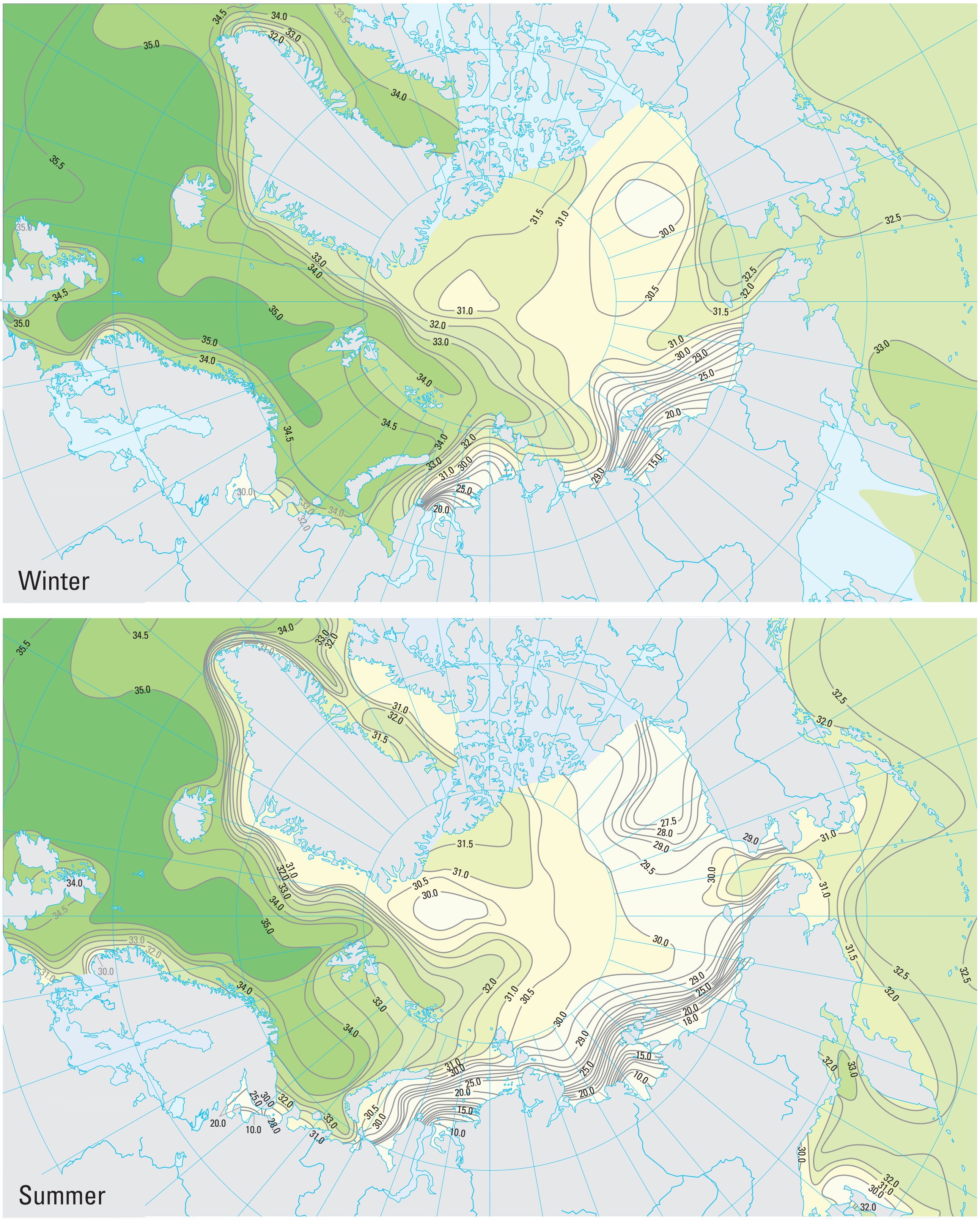

Figure 2·19. Winter and summer surface water salinity in the Arctic Ocean and adjacent seas (USSR Ministry of Defense 1980).

In general, surface water salinity in the Arctic Ocean and the adjacent shelf seas is relatively low compared to other oceans (Figure 2·19). In the Arctic Ocean itself, surface salinity varies between 30 and 33, and decreases in the area of the shelf seas to below 30. In general, the salinity is lower during summer than winter due to input of freshwater from rivers and ice melt. Close to where the large Russian rivers enter the Kara Sea and the Siberian shelf, the salinity is below 20 throughout the year and drops to as low as 10 during the summer (USSR Ministry of Defense 1980). The average total annual runoff of the Russian rivers is approximately 2100 km^3 (Aagaard and Carmack 1989). In the Canadian Arctic, the influence of the Mackenzie River is evident during summer, when the salinity drops to 27 in the surface layer. Salinity in the Arctic Basin increases with depth, reaching levels between 32.5 and 34.5 at 100 m (USSR Ministry of Defense 1980).

A more detailed description of the hydrographic conditions of the marine areas within the AMAP region is given in chapter 3, with more focus on vertical structure, mixing processes and transport of water masses.

Figure 2·20. Surface ocean currents in the Arctic.

2.6.3. Ocean currents

In a simplified picture, waters flowing north to the Arctic regions are comprised of warm currents originating from the Atlantic and Pacific Oceans, while cold currents flow out of the Arctic. Atlantic water enters the Arctic Ocean through Fram Strait and the Barents Sea, while Pacific water enters via Bering Strait. Water leaves the Arctic largely via Fram Strait, but also through the Canadian Arctic Archipelago (Macdonald and Bewers 1996) (Figure 2·20). Most of the water in the Arctic Ocean originates from the Atlantic Ocean (79%). The inflow through the Bering Strait is very modest (19%). The main water outflow is via the East Greenland Current (75%) and the outflow via the Canadian straits is relatively small (25%). Inflow from rivers represents only 2% and although this is a small percentage of the total, it is much higher than in other oceans (Sugden 1982). For further detail about Arctic currents, refer to chapter 3.

2.6.4. Sea ice

Sea ice forms from ocean water and floats on its surface. It forms when the temperature of the sea falls below the freezing point. The freezing point is dependent on the salinity of the seawater (–1.8°C for a salinity of 33) (Doherty and Kester 1974). The extent of ice cover changes with the seasons, with an average maximum of 15×10^6 km^2 in March and an average minimum of 8×10^6 km^2 in September (Gloersen *et al.* 1992) (see Figure 3·23).

In the Arctic Basin, it is possible to distinguish three different areas of sea ice: the drifting pack ice, the marginal ice zone and landfast ice. Perennial pack ice encompasses an area of approximately six million square kilometers. The pack ice is broken up by leads, which vary from 1% open water in winter to about 10-20% open water in summer (Gow and Tucker 1990). The ice, which averages between 2.5-4 m in thickness, is intersected by pressure ridges which are much thicker. The marginal ice zone is the region where pack ice meets the open water. This area shifts with the seasons, and is often an area of high biological productivity. Along the edges of many continents and archipelagoes, fast ice develops each year and extends offshore. The edge of this landfast ice is found at an ocean depth of about 22 m.

Flaw leads or coastal polynyas occur at the landfast ice border where offshore winds separate the drift ice from the pack ice. Polynyas are open water regions that persist within closed sea ice cover, ranging in area up to thousands of square kilometers. These areas often have a high rate of primary production of phytoplankton and are among the richest marine areas in the world. They represent areas of high energy exchange between ocean and atmosphere during the winter months when the sea ice cover effectively prevents exchange between water and air. Permanent polynyas have been found near Cape Bathurst (Beaufort Sea), Baffin Bay, northeastern Greenland and a region extending east and west of the northern part of the New Siberian Islands.

The two main ice circulation systems in the Arctic Basin are the clockwise Beaufort Gyre in the Amerasian Arctic, and the east to west Transpolar Drift in the Eurasian Arctic (Aagaard and Carmack 1989) (see Figure 3·23). Sea ice often circulates for more than five years in the Beaufort Gyre before being incorporated in the Transpolar Drift (Thorndike 1986, Rigor 1992). Most ice transported by the Transpolar Drift exits the central Arctic Basin through Fram Strait, although some is lost through the Barents Sea. Transport from the northern Kara Sea to Fram Strait may take as little as nine months, but averages two years (Rigor 1992, Pfirman *et al.* 1997).

The annual and year-to-year distribution of pack ice is determined by temperature, winds, and ocean currents, such as the Alaska Current, the Labrador Current, the East Greenland Current, the West Spitsbergen Current and the North Cape Current. Warm water transported north by the West Spitsbergen and North Cape Currents cause embayments in the ice distribution in the Greenland and Barents Seas. The North Cape Current also keeps the southern Barents Sea and the harbor of Murmansk free of ice during the winter. Sea ice is further discussed in chapter 3.

Acknowledgments

Editor

Janine L. Murray.

Authors

Janine L. Murray, Louwrens Hacquebord, Dennis J. Gregor, Harald Loeng.

Contributors

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