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Module 4
Physical Oceanography

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Key Terms and Concepts

- water mass
- thermocline
- halocline
- thermohaline circulation
- first-year sea ice
- multi-year sea ice
- sensible heat polynyas
- latent heat polynyas

Learning Objectives/Outcomes

This module should help you to

1. develop an understanding of the physiography of the Arctic Ocean basin and its marginal seas.
2. develop an understanding of the physical processes that influence the temperature and salinity of water masses formed in the Arctic Ocean basin and its marginal seas.
3. develop an understanding of the influence of atmospheric circulation on oceanic circulation and the interaction of water masses within polar seas.
4. develop an understanding of the physical processes that contribute to the growth and decay of sea ice and the formation of polynyas.
5. provide concise definitions for the key words.

Reading Assignments

Barry (1993), chapter 2: "Canada's Cold Seas," in *Canada's Cold Environments*, 29–61.

Coachman and Aagaard (1974), "Physical Oceanography of Arctic and Subarctic Seas," in *Marine Geology and Oceanography of the Arctic Seas*, 1–72.

Overview

The Arctic Ocean is a large ocean basin connected primarily to the Atlantic Ocean. An unusual feature of this ocean basin is the presence of sea ice. Sea ice covers less than 10% of the world's oceans and 40% of this sea ice occurs within the Arctic Ocean basin. There are several effects of this sea ice cover on the physical oceanography of the Arctic Ocean and its marginal seas (e.g., Baffin Bay, Hudson Bay, Barents Sea):

- The temperature of surface water remains near the freezing point for its salinity.
- Brine rejection from sea ice increases the density of surface waters and contributes to thermohaline circulation.
- Winds must transfer momentum from the atmosphere to the ocean surface through the sea ice cover.
- The seasonally variable albedo of sea ice affects the exchange of insolation at the ocean surface and the quantity of energy available to melt the sea ice cover.

This module examines the physiography of the polar seas, the physical processes that contribute to oceanic circulation and water mass formation, and the physical processes that influence the growth and decay of sea ice and the formation of polynyas.

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Lecture

Physiography of the Arctic Ocean Basin

The Arctic Ocean basin occupies an area of approximately 12 million square kilometres. Continental shelves occupy approximately 36% of the area of the ocean basin and are underlain by a considerable thickness of sedimentary rock. The Eurasian sector of the continental shelf is broad, extending up to 800 km from the coastline, with maximum water depths of 300–400 metres, and commonly less than 200 metres. In contrast, the North American sector of the continental shelf is narrow, extending 50–150 km from the coastline, with maximum water depths of 300–400 metres. (See fig. 4.1.)

Source: AMAP 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. GRID-Arendal.

Fig. 4.1 Physiography of the Arctic Ocean basin

Three oceanic ridges divide the Arctic Ocean basin into four separate basins. Moving from west to east, these ridges are known as the Alpha-Mendeleev Ridge, the Lomonosov Ridge, and the Arctic Mid-Oceanic Ridge (see fig. 4.1). Similarly, the basins are known as the Canada Basin, the Makarov Basin, the Amundsen Basin, and the Nansen Basin. Average water depths in the basins are approximately 4,000 metres, while minimum water depths over the ridges vary from 1,200 to 1,800 metres, so that the ridges rise 2,200–2,800 metres above the sea floor.

At the western boundary of the Arctic Ocean basin, the shallow Bering Strait, with water depths less than 45 metres, provides the only connection between the Pacific Ocean and the Arctic Ocean (see fig. 4.1). The channels of the Canadian Arctic Archipelago, notably Smith Sound, Jones Sound, Lancaster Sound, and Hudson Strait, connect the Arctic Ocean with the Atlantic Ocean via Baffin Bay and the Labrador Sea (see fig. 4.1). These inter-island channels are the products of subaerial exposure and stream erosion throughout the Tertiary period (1.65–66 million years BP). Maximum water depths within the channels of the archipelago vary from approximately 85 to 900 metres. Water depths within Foxe Basin, Hudson Bay, and James Bay vary from less than 50 to 200 metres. Water depths in Hudson Strait vary from 300 to 400 metres.

At the eastern boundary of the Arctic Ocean basin, a deep basin, the Greenland Sea, with maximum water depths of 2,600 metres, separates Greenland from the Svalbard archipelago and connects the Arctic Ocean to the Atlantic Ocean via the Denmark Strait; maximum water depths of 650 metres are recorded in the

Denmark Strait (see fig. 4.1). Further to the east, shallow channels, with water depths less than 200 metres, separate the Svalbard, Franz Joseph Land, and Novaya Zemlya archipelagos and connect the Arctic Ocean with the Atlantic Ocean via the Barents Sea. Maximum water depths in Barents Sea vary from 300 to 400 metres (see fig. 4.1).

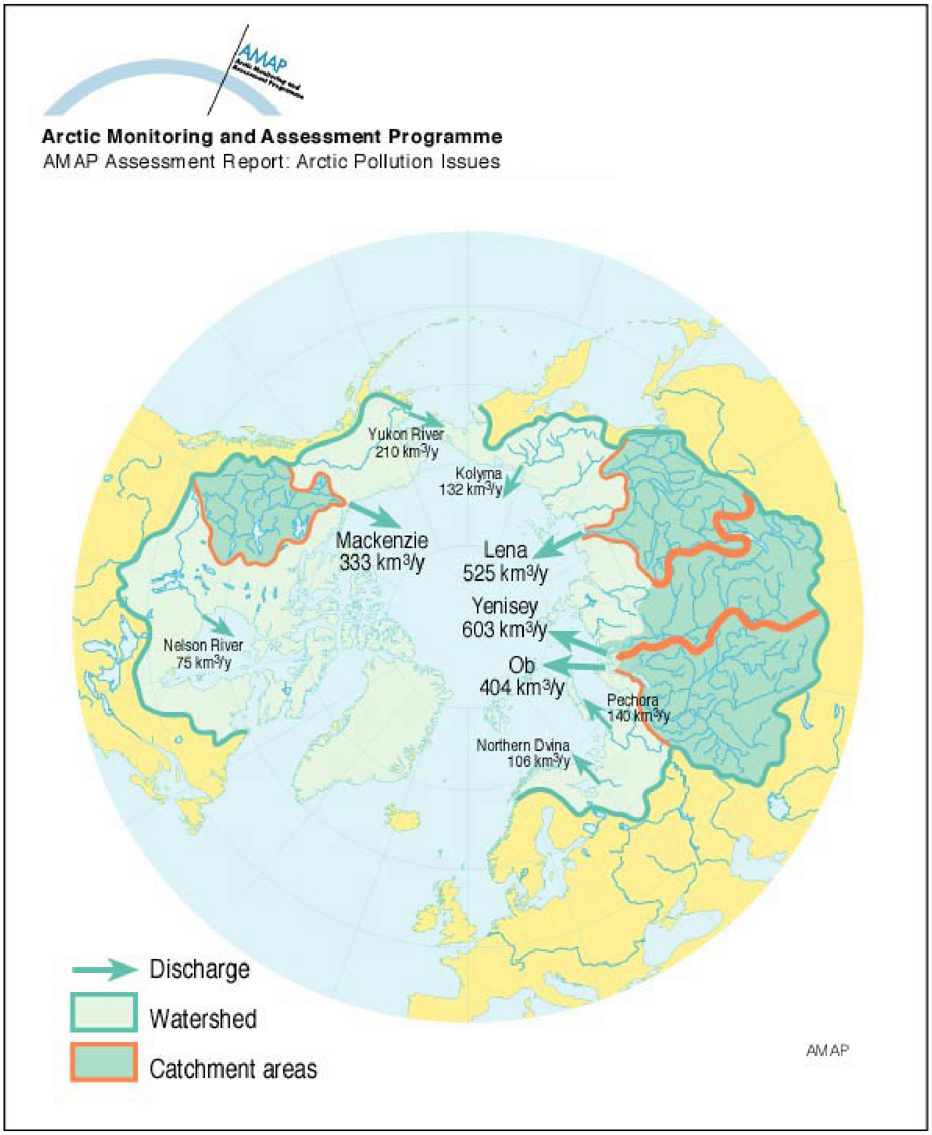
Water Masses

The fundamental physical characteristics of sea water are temperature, salinity, and density. Polar oceans are unusual in that water density is determined largely by variations in salinity, unlike elsewhere in the world's oceans, where variations in temperature are the determining factor.

The annual cycle of sea ice growth and decay significantly affects the temperature and salinity of surface waters in polar oceans. The transfer of sensible heat and sea ice by ocean currents, thermohaline circulation, and the exchange of energy between the atmosphere and ocean also modify the physical properties of surface waters in polar oceans. The most important of these various exchanges of mass and energy are as follows:

- the inflow and mixing of fresh water from the adjacent continents, primarily from several large Siberian rivers (i.e., Ob, Yenisei, Lena, and Kolyma) and the Mackenzie River
- the inflow and mixing of Pacific Ocean waters via Bering Strait and the Chukchi Sea
- the inflow and mixing of Atlantic Ocean waters via Norwegian and Barents seas
- the export of polar surface water and sea ice via the East Greenland Current,
- the absorption of insolation in ice-free areas during summer
- heat loss to the atmosphere through leads and polynyas during winter
- the increase in density of surface waters through brine rejection during the growth of sea ice

The first three exchanges primarily affect the salinity of polar surface waters. The lowest salinities are observed in proximity to the sources of inflowing freshwater, the Eurasian continental shelf, and the Canadian Mackenzie shelf (see fig. 4.2, fig. 4.3, and table 4.1). Salinities over these areas of the continental shelves vary from 27‰ (parts per thousand) to 30‰. It should be noted that this influx of freshwater and subsequent reduction in surface water salinities occurs only during the short summer season (see Module 3).



Source: AMAP 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Fig. 4.2 Freshwater discharge into the Arctic Ocean basin

Table 4.1 Examples of river discharge ($10^3 m^3 s^{-1}$) into the Arctic Ocean basin (adapted from Coachman and Aagaard 1974)

River	Maximum	Minimum	Average
Ob	20.8	13.5	16.3
Yenisei	20.5	16.8	19.2
Lena	19.9	13.6	16.2
Kolyma	5.6	2.4	4.2
Mackenzie	N/A	N/A	7.9

The highest salinities are associated with the inflow of Atlantic waters via the North Atlantic Drift and West Spitsbergen Current through the Norwegian and Barents seas, and via the Irminger and West Greenland currents into western Baffin Bay (see fig. 4.3). Salinities vary from 34‰ to 35‰ within the West Spitsbergen Current and from 31‰ to 34‰ within the West Greenland Current. The inflowing Atlantic water is denser than polar surface water and tends to sink along the continental slope as it enters the Arctic Ocean basin and Baffin Bay. Water derived from the Pacific Ocean is characterized by salinities ranging from 32‰ to 33‰.

Source: AMAP 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Fig. 4.3 Summer and winter surface salinities within the Arctic Ocean and its marginal seas

The exchange of sensible and latent heat between the atmosphere and ocean surface controls the temperature of polar surface waters (see fig. 4.4). The temperature of surface waters in the Arctic Ocean basin varies from –1.5°C to –1.8°C (i.e., the freezing point of sea water). As these surface waters move through the Canadian Arctic Archipelago and into Baffin Bay, the temperature increases gradually. Within the archipelago, polar surface waters exhibit temperatures ranging from 0°C to –1.8°C, while in eastern Baffin Bay, polar surface waters exhibit temperatures varying from 3°C to –1.8°C. Polar surface waters being exported from the Arctic Ocean basin via the East Greenland Current exhibit similar low temperatures.

Source: AMAP 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Fig. 4.4 Summer and winter surface temperatures within the Arctic Ocean and its marginal seas

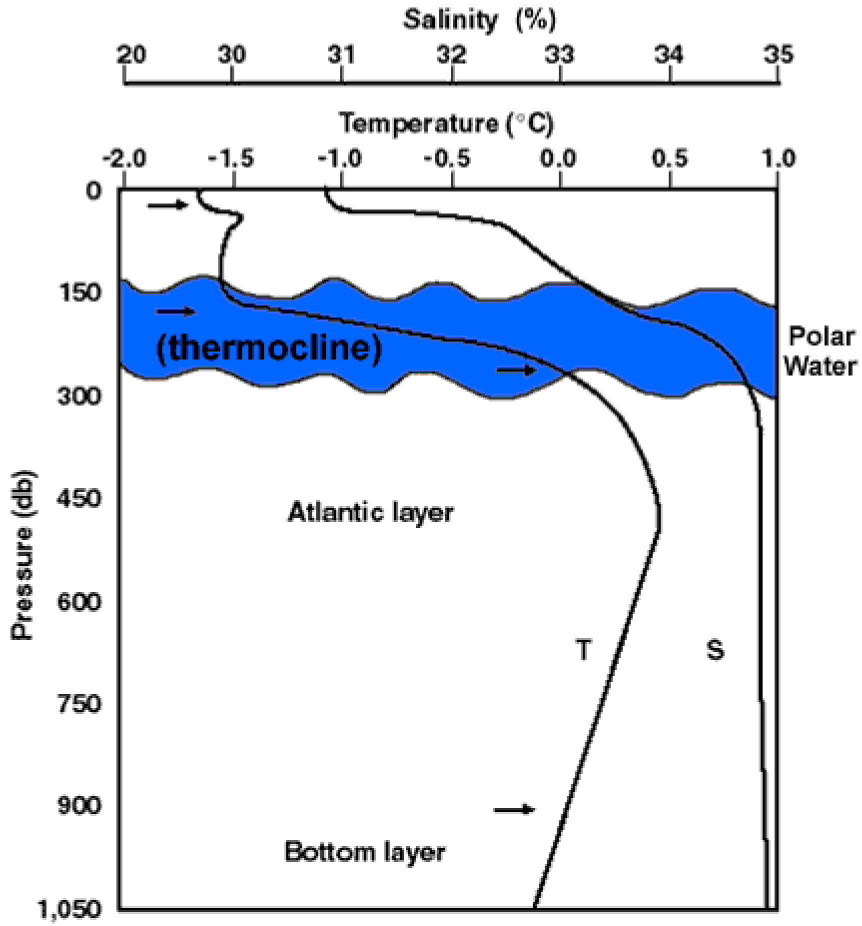
The combination of heat loss and brine rejection from sea ice during the winter season increases the density of polar surface waters and generates thermohaline circulation within the uppermost 200 metres of the ocean basin. Thermohaline circulation involves vertical currents that transport cold saline waters downwards from the ocean surface and transport warmer saline water, derived from underlying Atlantic waters, upwards to the ocean surface (see fig. 4.5). Winter temperatures of polar surface waters are near the freezing point (–1.5^{o}C to –1.8^{o}C) and salinities increase to 31‰ to 32‰ (see fig. 4.3 and fig. 4.4).

Source: AMAP 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Fig. 4.5 Thermohaline circulation within the Arctic Ocean and its marginal seas

The Arctic Ocean

Three water masses occur within the Canada Basin of the Arctic Ocean: Arctic Water, Atlantic Water, and Bottom Water. The shallow, well-mixed Arctic Water overlies a strong thermocline and halocline at 25–200 metres deep that separates surface waters from waters of Atlantic origin at greater depths (see fig. 4.6). The physical properties of Arctic Water are described in the preceding text. Temperatures of 0^{o}C to 0.5^{o}C and salinities of 34‰ to 35‰ characterize Atlantic Water within the Canada Basin. Bottom Water occurs at depths greater than 900 metres. Temperatures of –0.8^{o}C to –0.9^{o}C and salinities of 34‰ to 35‰ characterize Bottom Water within the Canada Basin.



Source: Adapted from Barry (1993)

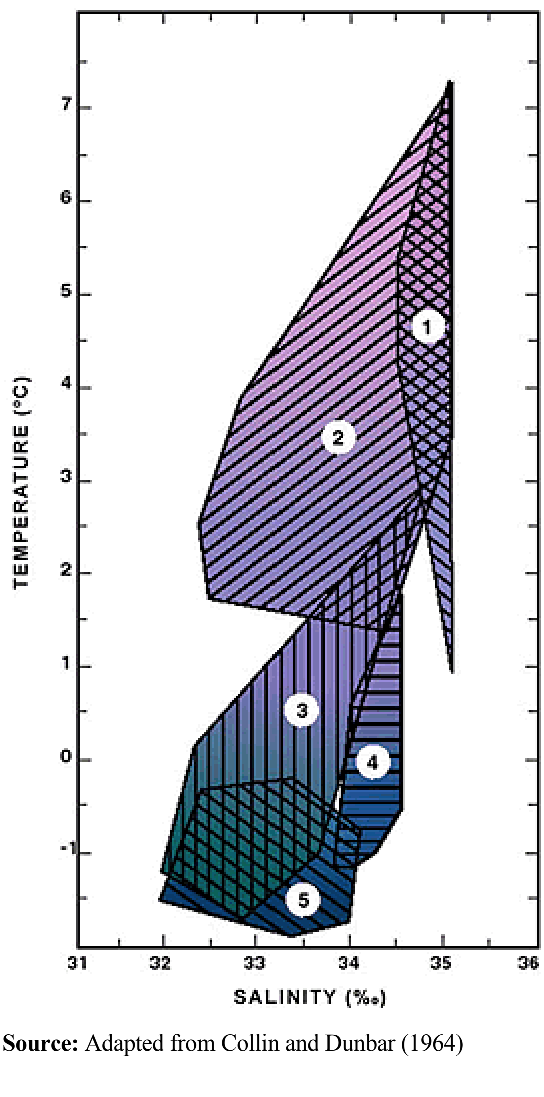
Fig. 4.6 Water mass characteristics within the Arctic Ocean basin

Canadian Arctic Archipelago

Arctic Water occurs at depths of 250–300 metres in channels within the archipelago. The surface water exhibits temperatures ranging from 0°C to –1.8°C and salinities ranging from 31‰ to 33‰. Beneath the surface water, Atlantic Water occurs at depths to 900 metres, with temperatures below 0°C and salinities of 34.65‰ to 34.85‰.

Baffin Bay and the Labrador Sea

Arctic Water enters northern and western Baffin Bay through channels in the Canadian Arctic Archipelago. The surface water occurs at depths of 200 metres and exhibits temperatures ranging from 1.8°C to –1.8°C and salinities ranging from 31‰ to 34‰. In eastern Baffin Bay, the inflow of Atlantic Water via the West Greenland Current generates surface water with temperatures ranging from 2°C to 5°C and salinities ranging from 32‰ to 34.5‰. The Atlantic Water flows across the continental shelf of west Greenland; however, Arctic Water occupies the continental shelf and upper slope along the coasts of Baffin Island and Labrador so that Atlantic Water is displaced to depths of 200 to 1,300 metres in this region. Here, the Atlantic Water exhibits temperatures of 0°C to 2°C and salinities from 34.2‰ to 34.5‰. Beneath the Atlantic Water lies Baffin Bay Deep Water with temperatures around 0°C and salinities from 34‰ to 34.5‰. Figure 4.7 illustrates the variations in the physical properties of the water masses observed in Baffin Bay and the Labrador Sea.



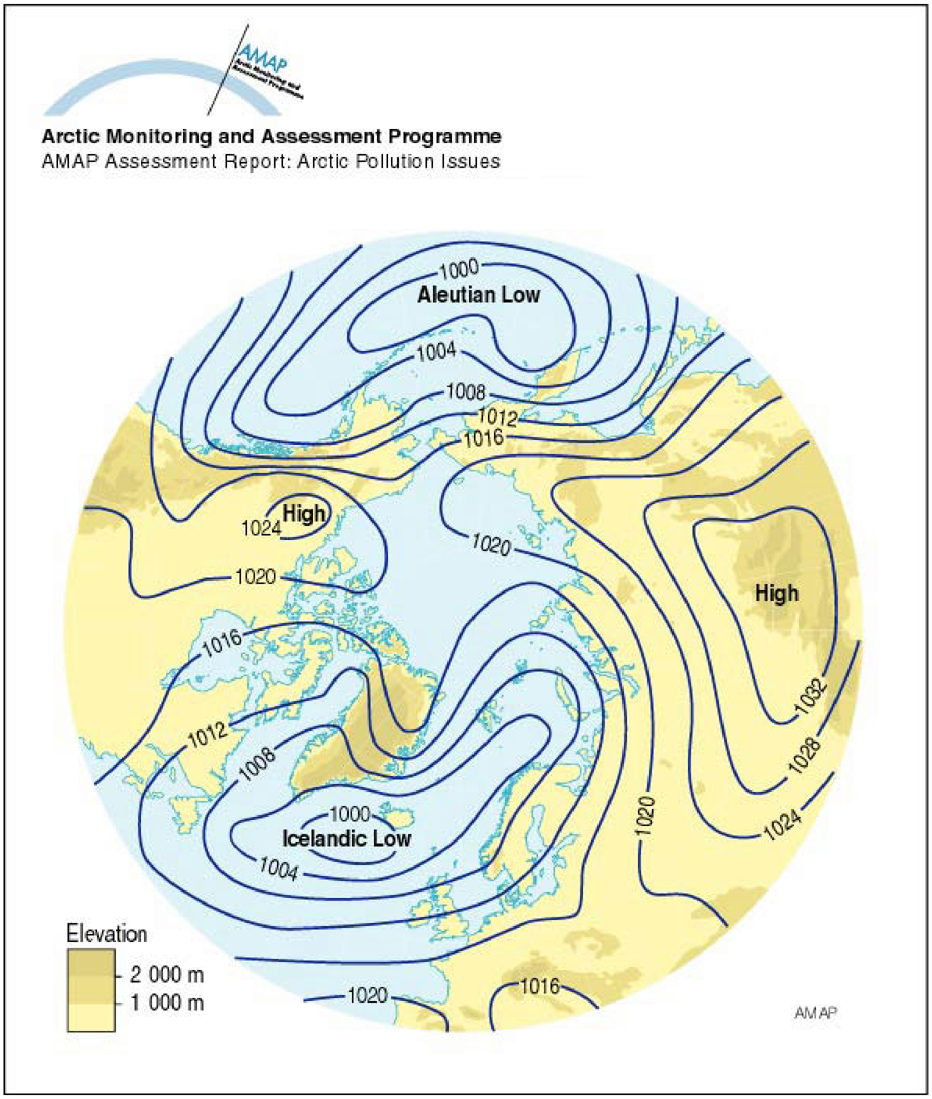
Source: Adapted from Collin and Dunbar (1964)

Fig. 4.7 Water mass characteristics within the Canadian Arctic Archipelago, Baffin Bay and the Labrador Sea. Legend: 1. Labrador Sea water; 2. West Greenland Current water;

3. Baffin Current and Labrador Current water; 4. Baffin Bay deep water; 5. Polar (Arctic) water

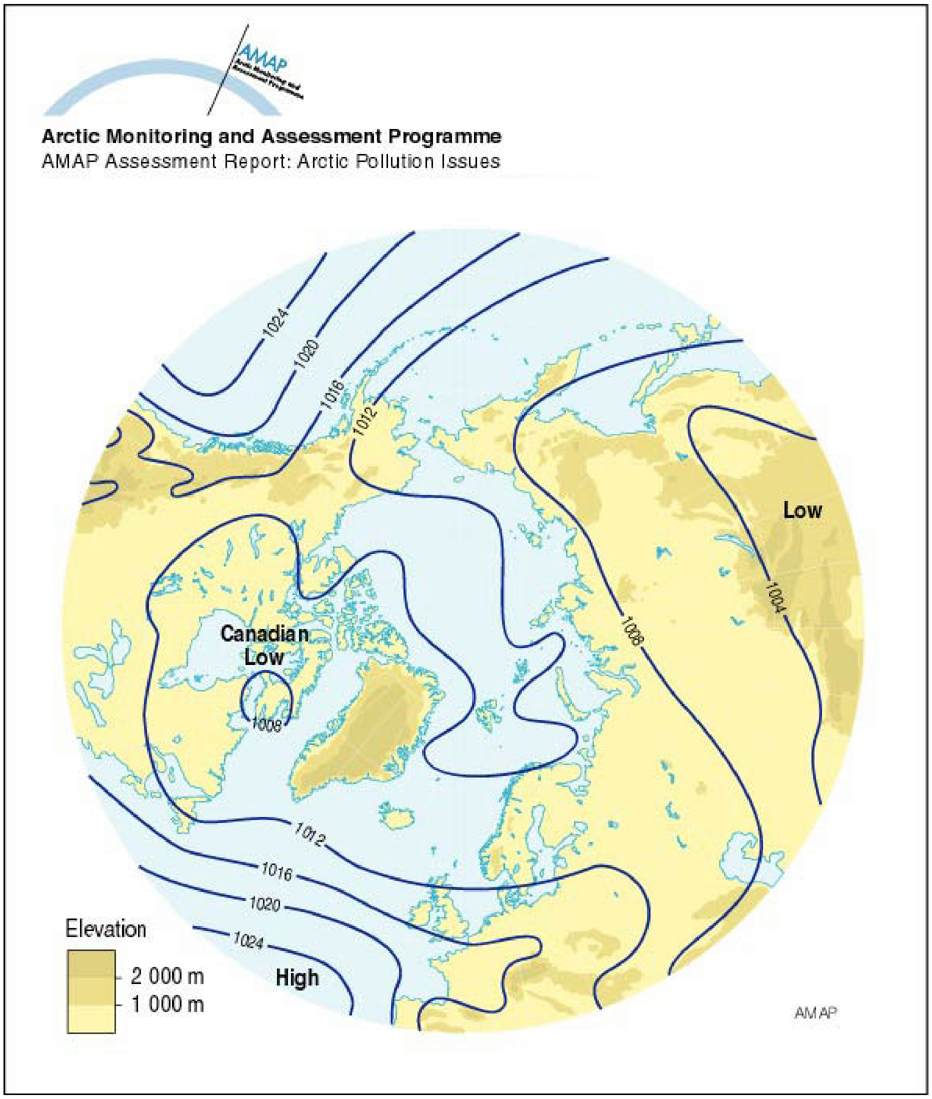
Ocean Circulation

Sea-level atmospheric pressure gradients and the corresponding wind fields are primarily responsible for driving ocean surface circulation. In the winter, regions of high atmospheric pressure develop over Siberia and the Canadian Arctic Archipelago, while regions of low atmospheric pressure develop over the North Atlantic and North Pacific oceans (see fig. 4.8). In contrast, during summer, a region of high atmospheric pressure develops over the central Arctic Ocean, while regions of low atmospheric pressure develop over the Labrador Sea and the Gulf of Alaska (see fig. 4.9). Atmospheric circulation about a region of high atmospheric pressure in the Northern Hemisphere is anticyclonic (clockwise). This flow of air drives the clockwise circulation of surface water in the Arctic Ocean basin represented by the Beaufort Sea Gyre and Transpolar Drift (see fig. 4.10). These surface currents move Arctic Water throughout the Arctic Ocean basin—to be discharged largely by the East Greenland Current into the North Atlantic Ocean (see fig. 4.10 and table 4.2).



Source: AMAP 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Fig. 4.8 January sea-level atmospheric pressure over the circumpolar North



Source: AMAP 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Fig. 4.9 July sea-level atmospheric pressure over the circumpolar North

Map Source: Base Map; Atlas of Canada (www.atlas.gc.ca), Government of Canada. **Data Source:** French and Slaymaker, 1993; AMAP Assessment Report: Arctic Pollution Issues. 1998 Arctic Monitoring and Assessment Program (AMAP). **Map produced by**: GIServices, University of Saskatchewan 2003. **Projection:** Azimuthal Equidistant. Latitude of Origin 75° N, Central Meridian 90° W. All latitudes north of the Equator.

Fig. 4.10 Ocean circulation within the Arctic Ocean basin and its marginal seas

Table 4.2 Water mass budget for the Arctic Ocean basin (adapted from Barry 1993)

		Inflow ($10^6 m^3 s^{-1}$)
Bering Strait		0.8
West Spitsbergen Current		3.6
Spitsbergen – Franz Joseph Land		0.7
Runoff from the continents		0.1
	Total	5.2

		Outflow ($10^6 m^3 s^{-1}$)
Canadian Arctic Archipelago		–1.7
East Greenland: Arctic Water		–1.8
Atlantic Water		–3.0
Sea Ice		–0.1
	Total	–6.6

Circulation through the Canadian Arctic Archipelago is generally to the south and southeast. Arctic Water is transported through several major inter-island channels to be discharged into Baffin Bay. These cold surface waters give rise to the Baffin Island Current that flows southwards across the continental shelf and upper slope off Baffin Island. (See fig. 4.10.). Arctic Water moving through Fury and Hecla Strait enters Foxe Basin and flows south into Hudson Bay. Circulation of surface waters in Hudson Bay is cyclonic (counter-clockwise) with outflow occurring through Hudson Strait (see fig. 4.10). The outflowing Arctic Water mixes with the Baffin Island Current to form the Labrador Current.

Atlantic Water enters the Arctic Ocean basin under the influence of the North Atlantic Drift and the West Spitsbergen Current (see fig. 4.10 and table 4.2). As noted above, inflowing Atlantic Water is denser than Arctic Water and tends to sink along the continental slope as it enters the Arctic Ocean basin. This water mass circulates counter-clockwise within the Arctic Ocean with outflow occurring beneath the East Greenland Current through the Greenland Sea (see fig. 4.10). The East Greenland Current mixes with Atlantic Water to form the Irminger Current, which then flows northward as the West Greenland Current (see fig. 4.10). The West Greenland Current circulates counter-clockwise within Baffin Bay, with outflow occurring beneath the Baffin Current into the Labrador Sea (see fig. 4.10).

The Chukchi Sea, the Beaufort Sea, Baffin Bay, the Labrador Sea, the Greenland Sea, and the Norwegian Sea are important regions for the mixing of Arctic and Atlantic waters and the transfer of sensible heat via ocean circulation (see Module 2). The Subarctic marine zone encompasses these regions of the northern oceans (see fig. 4.10).

Sea Ice and Polynyas

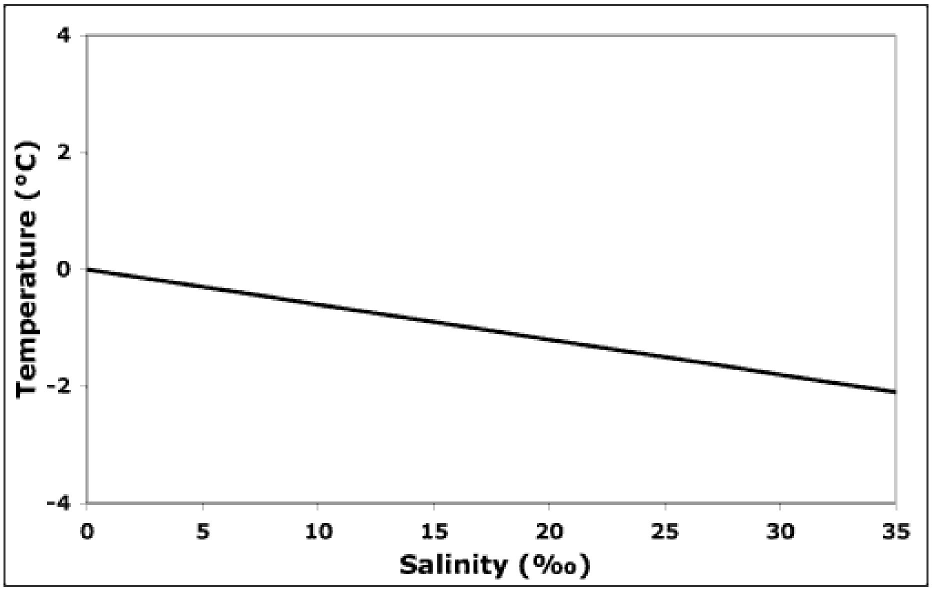
Growth and Decay of Sea Ice

The Arctic Ocean basin and its marginal seas experience large annual variations in sea ice cover. At its winter maximum, sea ice covers an area of roughly 16 million km^2, while at its summer maximum, the ice cover extends over roughly 8 million km^2 (see fig. 4.11).

Base Map Source: Canada; Atlas of Canada (www.atlas.gc.ca), Government of Canada. **Data Source:** AMAP Assessment Report: Arctic Pollution Issues. 1998 Arctic Monitoring and Assessment Programme (AMAP) and Atlas of Canada, North Circumpolar Region, 1999 Government of Canada with permission from Natural Resources Canada. **Map Produced by:** GIServices, University of Saskatchewan 2003. **Projection:** Azimuthal Equidistant. Latitude of Origin 75^{o} N, Central Meridian 90^{o} W.

Fig. 4.11 Annual variations in sea ice cover in the circumpolar North

The freezing point of water decreases from 0^{o}C for fresh water to –1.8^{o}C for sea water with a salinity of 35‰. In fact, the freezing point of sea water is a linear function of salinity (see fig. 4.12). As the surface of the ocean is cooled below the freezing point, small discs of frazil ice, approximately 2.5 cm in diameter, form and freeze together to form a continuous skin of pure ice crystals. Continued cooling of the ocean surface results in rapid vertical growth of these ice crystals. Most of the dissolved salts present in sea water are rejected from the growing sea ice cover; a process referred to as brine rejection. The rapid vertical growth of the ice cover traps the brine within small pockets (i.e., brine cells) within the sea ice. Newly formed sea ice exhibits salinities of 12‰ to 15‰. The brine drains slowly from sea ice under the influence of gravity and contributes to thermohaline circulation as discussed previously. Sea ice of not more than one winter's growth is referred to as first-year sea ice and can attain a thickness of 2–3 metres.



Source: Adapted from Barry (1993)

Fig. 4.12 Freezing point of sea water

The surface of first-year sea ice exhibits albedos of 0.7 to 0.8 (see Module 2); these high surface albedos affect the rate of sea ice melting via insolation in the succeeding summer. Early in the summer season, insolation is largely reflected off the sea ice surface, leaving little energy available to initiate melting of the sea ice. However, as surface melting proceeds, meltwater collects in pools on the ice surface. These meltwater pools lower the albedo of the sea ice surface to about 0.4. More insolation is absorbed within the pools than over the adjacent sea ice surface: this situation contributes to differential melting of the sea ice beneath the pools to create thaw holes. The development of thaw holes in sea ice facilitates the rapid drainage of surface meltwater and the flushing of brine, thereby reducing sea ice salinities to 2‰ to 4‰: at this stage sea ice can be melted to yield potable water. Differential melting and thaw-hole drainage creates hummocky topography on the surface of the sea ice. The meltwater released from sea ice is much less dense than the underlying sea water, and so it tends to accumulate directly beneath the melting ice cover, resulting in a reduction in surface water salinity. In situations where the energy available to melt sea ice is insufficient to melt the entire thickness of ice, masses of hummocky ice will persist on the sea surface. Sea water freezes to the base of the hummocky ice, as sea surface temperatures drop below the freezing point in the succeeding fall and winter, and begins a new period of sea ice growth. The cyclic process of surface melting and basal freezing continues as long as sea ice never completely melts. In this fashion, sea ice can attain a thickness of 5 metres. Sea ice that experiences two or more winter seasons is referred to as multi-year sea ice.

Polynyas

Numerous and recurrent polynyas and shore leads occur throughout the Canadian Arctic Archipelago (see fig. 4.13) and elsewhere about the margins of the Arctic Ocean basin. These are areas of open water and young ice less than 30 cm thick. The regions of polar oceans are maintained relatively free of sea ice by several physical processes, including currents, tides, and wind. Oceanographers distinguish between sensible heat polynyas and latent heat polynyas.

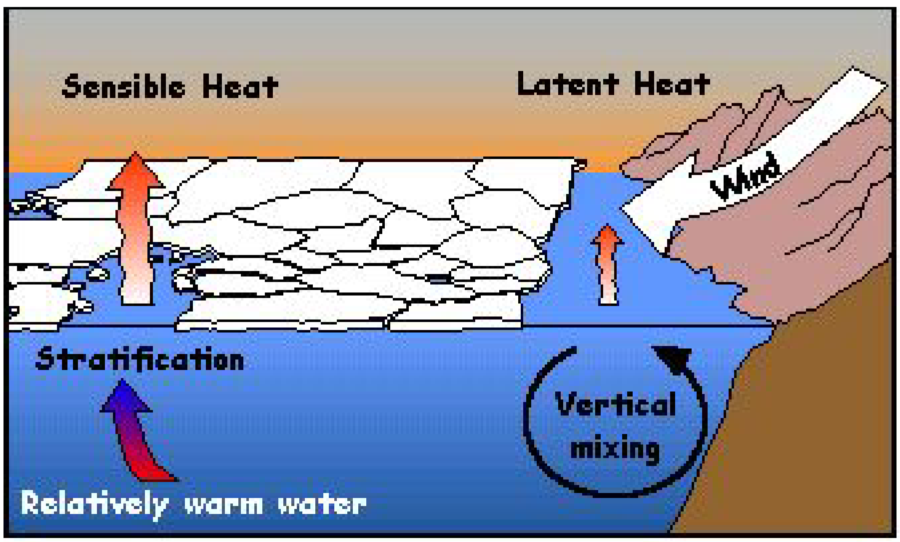
Fig. 4.13 Map illustrating the distribution of polynyas in the Canadian Arctic

Sensible heat polynyas form when deep, relatively warm water (>0^{o}C) derived from Atlantic Water rises towards the ocean surface, where it melts the sea ice cover or inhibits sea ice growth. The upwelling of warm water can occur when deep water is moved towards the surface to replace surface waters (i.e., Arctic Water) that have been transported away from land by persistent offshore winds (see fig. 4.14). Alternatively, turbulent mixing of water by currents and tides operating over shallow sills on the ocean floor can result in an upward mixing of Atlantic Water. In both cases, if sufficient sensible heat is transported towards the surface, a polynya will form. Small polynyas that occur within inter-island channels, such as those in Cardigan Strait, Bellot Strait, and Fury and Hecla Strait, are developed in the latter fashion.

Source: International North Water Polynya Study (NOW), http://www.fsg.ulaval.ca/giroq/now/gallery.htm

Fig. 4.14 Ocean surface of the North Water polynya illustrating drifting icebergs and small quantities of sea ice

Latent heat polynyas form in areas where sea ice is transported away by winds and currents as soon as it has formed, thus reducing the quantity of sea ice present at the ocean surface (see fig. 4.15). A tremendous amount of energy, in the form of latent heat, is lost from surface waters to the atmosphere during the formation of sea ice within these polynyas. Vigorous growth of sea ice is accompanied by brine rejection into the underlying cold surface water. The mass of cold saline water produced in this fashion tends to sink in the process of thermohaline circulation, displacing warmer Atlantic Water upwards to ocean surface. The upwelling of warmer water contributes to maintaining an open water surface. Large polynyas, such as the North Water and Cape Bathurst polynyas, develop in this fashion.



Source: International North Water Polynya Study (NOW), http://www.fsg.ulaval.ca/giroq/now/gallery.htm

Fig. 4.15 Ocean-atmosphere circulation within polynyas

Summary

The Arctic Ocean is a deep basin (maximum water depths exceed 4,000 m) surrounded by broad continental shelves (maximum water depths of 300 to 400 m). This ocean basin is linked to the Pacific Ocean via the shallow waters of Bering Strait (maximum water depths are less than 45 m), and to the Atlantic Ocean via the deep waters of the Greenland Sea (maximum water depths of 2,600 m) and Denmark Strait (maximum water depths of 650 m) and the shallow channels (maximum water depths less than 200 m) within the Canadian Arctic and Svalbard archipelagos.

Atmospheric circulation is primarily responsible for driving ocean surface circulation. Anticyclonic (clockwise) flow in the atmosphere over the Arctic Ocean basin initiates the clockwise circulation of surface water in the Arctic Ocean basin represented by the Beaufort Sea Gyre and Transpolar Drift. These surface currents move Arctic Water, characterized by temperatures of $-1.8^{o}C$ to $3^{o}C$ and salinities of 31‰ to 34‰, across the Arctic Ocean basin to be discharged largely by the East Greenland Current and the Baffin Current into the North Atlantic Ocean.

Atlantic water enters the Arctic Ocean basin under the influence of the North Atlantic Drift and the West Spitsbergen Current. The inflowing Atlantic Water is denser (temperatures vary from $0^{o}C$ to $5^{o}C$, and salinities vary from 32‰ to 35‰) than Arctic Water and tends to sink along the continental slope as it enters the Arctic Ocean basin. This water mass circulates counter-clockwise within the Arctic Ocean, with outflow occurring beneath the East Greenland Current through the Greenland Sea. The East Greenland Current mixes with Atlantic Water to form the Irminger Current, which then flows northward as the West Greenland Current. The West Greenland Current circulates counter-clockwise within Baffin Bay, with outflow occurring beneath the Baffin Current into the Labrador Sea.

Sea ice is a prominent feature of polar seas; and 40% of the world's sea ice occurs within the Arctic Ocean basin. The Arctic Ocean basin and its marginal seas experience large annual variations in sea ice cover. At its winter maximum, sea ice covers an area of roughly 16 million km^2, while at its summer maximum, the ice cover extends over roughly 8 million km^2. The effects of this sea ice cover on the physical oceanography of the Arctic Ocean and its marginal seas are several: the temperature of surface water remains near the freezing point for its salinity; brine rejection from sea ice increases the density of surface waters and contributes to thermohaline circulation; winds must transfer momentum from the atmosphere to the ocean surface through the sea ice cover; and the seasonally variable albedo of sea ice affects the exchange of insolation at the ocean surface and the quantity of energy available to melt the sea ice cover. Numerous and recurrent polynyas and shore leads occur about the margins of the Arctic Ocean basin. These are areas of open water and young ice less than 30 cm thick. The regions of polar oceans are maintained relatively free of sea ice by several physical processes, including currents, tides, and wind.

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Study Questions

A. Multiple Choice Questions

1. The West Spitsbergen Current exhibits these physical characteristics:
   a. warm temperature (>0°C), low salinity (<34‰)
   b. cold temperature (<0°C), low salinity (<34‰)
   c. warm temperature (>0°C), high salinity (>34‰)
   d. cold temperature (<0°C), high salinity (>34‰)

2. The Baffin Current exhibits these physical characteristics:
   a. warm temperature (>0°C), low salinity (<34‰)
   b. cold temperature (<0°C), low salinity (<34‰)
   c. warm temperature (>0°C), high salinity (>34‰)
   d. cold temperature (<0°C), high salinity (>34‰)

3. The term "frazil" describes ______________________.
   a. the rapid increase in stream discharge following snow melt
   b. a body of open water within multi-year sea ice
   c. the initial growth phase of first-year sea ice
   d. the change in the surface albedo of first-year sea ice due to melting

4. Thermohaline circulation describes ______________________.
   a. the motion of Arctic Water via the Transpolar Drift
   b. the mixing of oceanic surface waters associated with the growth of sea ice
   c. the motion of Atlantic Water via the East Greenland Current
   d. a rapid increase in river discharge in the late spring in northern environments

5. Circulation of Arctic Water within the Arctic Ocean basin is best described as ______________________.
   a. anticyclonic (clockwise)
   b. cyclonic (counter-clockwise)
   c. upwelling
   d. thermohaline

Answers to Multiple Choice Questions

1. c.
2. b.
3. c.
4. b.
5. a.

B. Essay Question

In an essay, describe the processes that contribute to the physical properties (temperature, salinity, and density) of water masses in the Arctic Ocean and the Labrador Sea.

Glossary of Terms

leads	a channel of water in an icefield.
polynya	a stretch of open water and young ice less than 30 cm thick, esp. in the Arctic seas.
shore lead	areas of open water and new or young ice less than 30 cm thick that develop parallel to coastline.
thermohaline circulation	vertical mixing of water masses caused by differences in densities associated with variations in temperature and salinity.
water mass	a large volume of water with unique properties of temperature, salinity, and density that extends horizontally over thousands of kilometres.

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