978-0-521-85010-0 — Climate Change in the Polar Regions
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Excerpt
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Introduction

1.1 The environment of the polar regions

The polar regions can be defined in a number of ways, based on geographical, topographic and even political factors. However, geometrically, the Arctic and Antarctic are considered as the areas of the Earth poleward of the Arctic and Antarctic Circles, which are located at latitudes of 66° 33′ 39″ north and south of the Equator (see maps on the end papers). These areas experience at least one day each year when the Sun does not set, and one day when the Sun is always below the horizon. At the poles themselves there is only one sunrise and one sunset each year, which occurs on the equinoxes of 21 September and 21 March. Together the Arctic and Antarctic comprise about 8% of the surface area of the Earth.

The regions of perpetual summer sunlight and winter darkness are present because the Earth is tilted away from the plane of its orbit around the Sun by 23° 27′, resulting in the high latitude areas having periods when they are orientated away from or towards the Sun. The tilt of the Earth's axis changes over long periods of time (millennia), resulting in variations in the latitude of the Arctic and Antarctic Circles. The change in the tilt, along with slow variations in the Earth's orbit about the Sun, alter the amount of solar radiation arriving at different parts of the Earth, which is a major factor in long-term, millennial-scale climate variability. This subject is covered in depth in Section 3.4.

The Arctic Circle runs through the North Atlantic, southern Greenland, northern Canada, central Alaska, northern Russia and northern Fennoscandia. The Antarctic Circle by contrast is primarily located over the Southern Ocean, only crossing the Antarctic continent on the Antarctic Peninsula, and in the northern edges of Enderby Land, Wilkes Land and George V Land.

In the polar regions the Sun always has a relatively low elevation during the summer, never reaching more than about 23° above the horizon. The instantaneous amount of solar radiation received at the top of the atmosphere is therefore quite small, and much less than occurs in tropical latitudes where the Sun is nearly overhead.

A number of factors influence the amount of solar radiation that is absorbed by the surface and is therefore available to heat the ground or ocean, or melt snow and ice. Although the Sun is low in the sky in summer, the high latitude atmosphere is relatively clear (especially in the Antarctic) with few suspended particles (aerosols) that can scatter or reflect the incoming radiation. The amount of water vapour in the atmosphere is also quite low, especially on the Antarctic Plateau, so the amount of radiation absorbed by this gas is very limited. However, a major factor in influencing the amount of radiation arriving at the surface is the length of the period of sunlight. On the Antarctic Plateau the long period of continuous daylight, coupled with the clear, frequently cloud-free atmosphere means that this region receives more solar radiation than anywhere else on Earth. Nevertheless, the lowest temperature ever recorded at the surface of the Earth was at Vostok Station (78.5° S, 106.9° E, 3488 m) high on the plateau.

Although large amounts of solar radiation can be received at the surface in summer, much of this insolation is reflected back to space because of the high albedo (reflectivity) of the snow and ice surfaces. Freshly fallen snow can have a very high albedo of 90%, but this drops as the snow pack ages, typically reaching values of 80%. Exposed glacier ice (known as blue ice) typically has an albedo of around 70%. Snow with dust particles on the surface will have a lower albedo, and as snow melts, gradually exposing the rock or soil surface below, the albedo will gradually drop to that of bare ground, which is typically 15–20%. The Antarctic Plateau is therefore a unique location, receiving large amounts of solar radiation in summer, most of which is reflected back to space, resulting in the lowest summer temperatures on Earth.

In the sea ice zone the surface consists of a mix of ice floes that typically have an albedo of 70–80% and open water with an albedo of 10–15%. So the fractional ice cover is critical in determining the amount of solar radiation that is absorbed by the surface. A major difference between the Arctic and Antarctic is the amount of multi-year sea ice (sea ice that has survived one summer) that is present. In the Antarctic most sea ice melts by the late summer, with only small amounts of ice persisting into the following winter along the coast of East Antarctic and over the western Weddell Sea. In the Arctic, however, there is a higher proportion of multi-year ice present.

During periods when solar radiation is received, a number of different ‘polar feedback’ mechanisms can come into play, which can amplify small environmental changes. For example, in the case where the ocean is partially covered by sea ice, once the fractional ice cover has dropped to a certain level, enough solar radiation may be received to warm the upper layers of the ocean, resulting in the rapid melting of the remaining sea ice in a region. This is often the case along the coast of Dronning Maud Land, on the eastern side of the Weddell Sea, Antarctica, where there can be a rapid expansion of the coastal polynya (the ice-free region next to the coast) during December. A similar positive feedback is found over snow-covered land areas during the high latitude spring, where the snow can rapidly retreat once enough bare ground is exposed and sufficient heat has been absorbed by the surface. This takes place across northern Eurasia and results in extensive river runoff into the Arctic Ocean.

As discussed in later chapters, many projections of future climate suggest that the largest increases in near-surface air temperature will occur at high latitudes, possibly as a result of feedback mechanisms. We will therefore return in later chapters to the question of whether such mechanisms are responsible for recent Arctic and Antarctic climate change, and the role that they may play in the future.

During the long polar winter, environmental conditions are quite different from the summer months. The lack of solar radiation, coupled with the relatively dry atmosphere (especially in the Antarctic) results in rapid cooling near the Earth's surface and the creation of an atmospheric temperature inversion, where the temperature increases with height for several hundreds of metres or more. The most pronounced temperature inversions are found on the Antarctic Plateau, where the temperature difference between the surface and an elevation of a few hundred metres can be in excess of 25 °C. Over the Arctic Ocean in winter there is still a sizeable flux of heat from the ocean into the lowest layers of the atmosphere, either through the sea ice or more often via the leads (the ice-free areas between the ice floes). This limits the strength of the temperature inversion in these maritime areas.

This section has been concerned with climatic and environmental factors that are common to both polar regions. However, in the next section we focus on some of the striking differences in the climates of the Arctic and Antarctic that result from the markedly different land/sea distributions and orographic conditions in the two polar regions.

1.1.1 The Arctic

The Arctic (see the front end paper) consists of the Arctic Ocean, a number of islands and archipelagos, and the northern parts of North America, Greenland, Russia and Scandinavia. The huge ice sheet of Greenland extends to over 3 km in height and contains about 3×10^6 km^3 of ice. It has a major impact on the atmospheric circulation of the North Atlantic and its climatological effects can be felt well into Europe. However, the rest of the orography of the Arctic is relatively low, and there are extensive ocean areas around the Arctic, such as the Greenland Sea, so that mid latitude weather systems can penetrate to high latitudes. As maritime air masses move northwards and are cooled, extensive areas of cloud form, influencing the radiation regime. The Arctic is therefore characterised by rather cloudy conditions, although as the air is fairly cold it is unable to hold a great deal of water vapour, so precipitation amounts tend to be relatively low. For example, Barrow, Alaska, only receives about 115 mm of precipitation per year, compared with London, which on average gets almost 600 mm a year.

The proximity of the Arctic to major industrial centres in Europe and Eurasia means that atmospheric pollutants, such as sulphates, can readily reach northern high latitudes. This phenomenon, which is known as Arctic haze, is seasonal in nature with a peak in the spring once the Sun returns after the long Arctic winter. The pollutants are apparent as a brownish haze that can reduce the visibility to less than 30 km and the aerosols that make up Arctic haze can have an impact on climate forcing, and also contaminate the fragile Arctic ecosystems and food chains.

At the heart of the Arctic is the Arctic Ocean, which covers an area of 14.09×10^6 km^2, making it the smallest of the world's oceans. It lies almost entirely within the Arctic Circle and is mostly surrounded by land, with its only outlets being the Bering Strait between Alaska and Russia, the Davis Strait between Greenland and Canada, and the Denmark Strait and the Norwegian Sea between Greenland and Europe. However, the only deep passage out of the Arctic Ocean is the Fram Strait between Greenland and Spitsbergen, which has a major influence on the exchange of water masses with the rest of the world's oceans. The ocean has an average depth of 3658 m off the continental shelf and the deepest point is the Fram Basin at a depth of 4665 m. The Arctic Ocean has the widest continental shelf of all the oceans. The Arctic Ocean is divided by the Lomonosov Ridge into two major basins, consisting of the Eurasian Basin and the North American Basin, both of which have a depth in excess of 4300 m.

The Arctic Ocean contains three primary water masses. In the near-surface layer, which is up to 200 m thick, there is Polar Surface Water, above warm Atlantic Water, with Arctic Ocean Deep Water below about 800 m. Polar Surface Water has a low salinity as a result of the very large input of fresh water from the major river systems that issue into the Arctic Ocean, such as the Lena, Yenisey and Mackenzie.

Sea ice is a major feature of the Arctic and it has a profound impact on the meteorology and oceanography of the entire Arctic region. Sea ice forms when the upper layer of the ocean freezes during the winter to form new or first-year ice. It is during late winter, around the March/April period, that Arctic sea ice reaches its maximum extent of about 15×10^6 km^2, covering most of the Arctic Ocean and extending into the neighbouring seas. During the summer months there is extensive melting of sea ice and by September it has retreated to cover about half the area of its late-winter peak. Multi-year sea ice can reach thicknesses of several metres. In recent years there has been a well-publicised decrease in the amount of Arctic sea ice, and climate projections for the next century suggest that the area covered by sea ice will continue to shrink. This subject will be discussed in detail in Chapters 6 and 7.

The near-surface ocean currents and the motion of the sea ice within the Arctic Ocean are essentially the same, and are characterised by the anticyclonic Beaufort Gyre poleward of North America and the Transpolar Drift that extends from the northern coast of Siberia to the Fram Strait and down the east coast of Greenland.

The land surrounding the Arctic Ocean is characterised by tundra, boreal forests, peatlands and permafrost (permanently frozen ground). The boreal forest or taiga consists of coniferous trees and is located on the edges of the Arctic, with the northern limit roughly following the July mean 13 °C isotherm. The forest edge therefore extends from roughly 68° N in the Brooks Range of Alaska to 58° N on the west coast of Hudson Bay. In Siberia the tree limit is further south, some 500 km inland of the Siberian Sea.

North of the boreal forest is the treeless Arctic tundra, consisting of low shrubs, mosses and lichens, which can exist in an environment with a short growing season. Although the tundra has low species diversity, it supports large populations of wild and semi-domestic animals. Figure 1.1 shows a tundra landscape in the Denali National Park, Alaska.

The tundra is characterised by persistent winter snow cover and frozen ground. Snow depth is typically 30–40 cm, reflecting the limited capacity of the air to hold moisture and the remoteness of many parts of the Arctic from open water that can supply moisture to the air

Fig. 1.1 The tundra landscape in the Denali National Park, Alaska.

masses. During the short Arctic spring much of the snow cover melts, feeding the many rivers that discharge fresh water into the Arctic Ocean.

Permafrost, as well as seasonally frozen ground, is found across much of the Arctic. Permafrost consists of gravel and finer material that remains below the freezing point throughout two or more consecutive years. This layer of permanently frozen subsoil can be overlaid with unfrozen soil or organic material. When water saturates the upper surface, bogs and ponds may form, providing moisture for plants. The presence of permafrost means that there are no deep root systems in the vegetation of the Arctic tundra; however, a wide variety of plants are still able to resist the cold conditions. Ice-rich permafrost is found beneath about 80% of Alaska and it physically supports much of the state's infrastructure and natural ecosystems. Figure 1.2 illustrates an active ice wedge, which shows permafrost visible at the surface.

Permafrost is present across almost a quarter of the Earth's land area, with some 16.7×10^6 km^2 being present in northern Russia and Scandinavia, and 10.2×10^6 km^2 in North America. Most of the Arctic islands also contain permafrost. The thickness of permafrost varies from about 1500 m in some parts of Siberia and almost 750 m in northern Alaska, to only a few metres on the edge of the Arctic.

A major difference between the Arctic and Antarctic is that the Arctic is home to many indigenous peoples, while the Antarctic is only occupied by scientists and tourists who visit the continent for periods of days or weeks, up to several years. In the north, Inuit, Saami, Athapaskans, Nenets and other peoples have followed a traditional way of life for generations, often subsisting by hunting on land or through fishing. Many of the activities of these

Fig. 1.2 An active ice wedge exposed by hydraulic trenching at the northwest arm of Kaminak Lake, Kivalliq, Nunavut, Canada. (Photograph courtesy of Dr William W. Shilts.)

peoples are very dependent on the climate and, as discussed below, climate change in the future may have a radical impact on their way of life.

1.1.2 The Antarctic

Politically, the Antarctic is defined as the area south of 60° S and it includes the Antarctic continent, a number of the sub-Antarctic islands and a large part of the Southern Ocean (see back end paper).

The Antarctic continent is about 40% larger than the USA, covering an area of 13.6×10^6 km^2, which is about 10% of the land surface of the Earth. This figure includes the area of the ice sheet, the floating ice shelves and the areas of fast ice (sea ice frozen along the coast).

The continent is dominated by the Antarctic Ice Sheet, which contains around 30×10^6 km^3 of ice or about 70% of the world's fresh water. The Antarctic has the highest mean elevation of any continent on Earth, and reaches a maximum elevation of over 4000 m in East Antarctica.

The ice sheet is made up of three distinct morphological zones, consisting of East Antarctica (covering an area of 9.90×10^6 km^2), West Antarctica (1.96×10^6 km^2) and the Antarctic Peninsula (0.39×10^6 km^2). The orography rises very rapidly inland from the coast and the continent has a domed profile, with much of it being above 2000 m in elevation.

The high plateau of East Antarctica is where the lowest recorded temperature on Earth has been measured. At the Russian Vostok Station on 21 July 1983 the temperature dropped to −89.2 °C, although as parts of the continent are at an even higher elevation it is not inconceivable that a near-surface temperature several degrees colder might one day be measured in the Antarctic. The extremely low temperature occurred at Vostok because of the very high elevation, the lack of cloud and water vapour in the atmosphere, and the isolation of the region from the relatively warm maritime air masses found over the Southern Ocean. The high plateau of East Antarctica is located slightly away from the South Pole and this has climatological implications for the atmospheric circulation over the Southern Ocean.

The very cold temperatures in the interior of the Antarctic, coupled with its isolation from warm, moist air masses mean that precipitation amounts here are very low, with only about 50 mm water equivalent falling per year. The Antarctic is therefore a desert and the driest continent on Earth. But the low temperatures mean that there is very little evaporation and sublimation, so that even this small amount of precipitation builds up year by year to form the ice sheet.

West Antarctica is lower than East Antarctica, with a mean elevation of 1119 m. However, some areas do reach more than 2000 m in height, with exposed mountain peaks rising above the ice sheet to more than 4000 m. East and West Antarctica are separated by the Transantarctic Mountains, which extend from Victoria Land to the Ronne Ice Shelf and rise to a maximum height of 4528 m.

The Antarctic Peninsula is the only part of the continent that extends a significant way northwards from the main ice sheet. It is a narrow mountainous region with an average width of 70 km and a mean height of 911 m. The northern tip of the peninsula is close to 63° S, so that this barrier has a major influence on the oceanic and atmospheric circulations of the high southern latitudes.

In the Antarctic coastal region temperatures are much less extreme than on the plateau, although at most of the coastal stations temperatures rarely rise above freezing point, even in summer. The highest temperatures on the continent are found on the western side of the

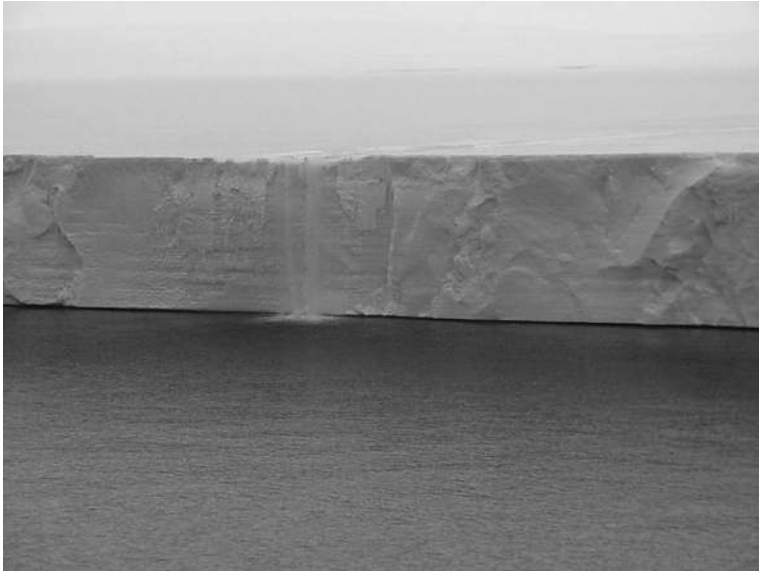

Fig 1.3 A photograph of the edge of part of the Larsen B Ice Shelf before its disintegration.

Antarctic Peninsula where there is a prevailing northwesterly wind, and here temperatures can rise several degrees above freezing during the summer months.

The Antarctic Ice Sheet has a maximum thickness of about 4700 m and this huge mass of ice gradually flows down towards the edge of the continent, moving fastest in a number of ice streams that travel at speeds of up to 500 m per year. Once the ice streams reach the edge of the continent they either calve into icebergs, which move northwards, or start to float on the ocean as ice shelves. The ice shelves constitute 11% of the total area of the Antarctic, with the two largest shelves being the Ronne-Filchner and the Ross Ice Shelves, which have areas of 0.53×10^6 km^2 and 0.50×10^6 km^2 respectively. The ice shelves are several hundreds of metres thick and the ocean areas under them are important for the formation of cold, dense Antarctic Bottom Water (AABW), which is discussed in Section 1.2. Figure 1.3 shows part of the Larsen B Ice Shelf before its disintegration.

The Antarctic continent is surrounded by the sea ice zone where, by late winter, the ice covers an average area of 19×10^6 km^2, which is more than the area of the continent itself. At this time of year the northern ice edge is close to 60° S around most of the continent, and near 55° S to the north of the Weddell Sea. Unlike the Arctic, most of the Antarctic sea ice melts during the summer so that by autumn it only covers an area of about 3×10^6 km^2. Most Antarctic sea ice is therefore first-year ice, with the largest area of multi-year ice being over the western Weddell Sea. Consequently most sea ice around the continent is relatively thin, with an average thickness of about 1–2 m.

Permafrost is much less extensive in the Antarctic compared with the Arctic, because of the very large area covered by the ice sheet. However, across parts of the Antarctic Peninsula and on the sub-Antarctic islands there are extensive areas that are free of ice and snow during the summer months. Here permafrost and seasonally frozen ground are significant features of the environment and they are important in the support of terrestrial ecosystems. Permafrost is also found in the McMurdo Dry Valleys and along the narrow coastal zone of East Antarctica. The Dry Valleys are a particularly interesting area where liquid water is rare, yet there are extensive ground ice glacial sediments that may be millions of years old. Permafrost is also found under the Antarctic Ice Sheet itself.

The major societal difference between the Arctic and Antarctic is the lack of indigenous peoples in the south. Here the only year-round residents are scientists who work on the research stations. Typically only a few hundred scientists overwinter on the stations, but this number swells to several thousand during the summer Antarctic season. In recent years there has been a very large increase in the number of tourists visiting the continent, either by cruise ship or flying to the Antarctic from South America. The International Association of Antarctic Tour Operators, who aim to promote safe and environmentally responsible private-sector travel to the Antarctic, reports that during the 2006–07 Antarctic summer 29 530 tourists visited the continent. This compares with only 6000 in the early 1990s. Such a huge increase in the number of tourists visiting the continent, and the possibility of these numbers increasing markedly in the coming years, will inevitably put pressure on the fragile environment of the continent.

1.2 The role of the polar regions in the global climate system

The global climate system is driven by solar radiation, most of which on an annual basis arrives at low latitudes. Over the year as a whole the Equator receives about five times as much radiation as the poles, so creating a large Equator to pole temperature difference. The atmospheric and oceanic circulations respond to this large horizontal temperature gradient by transporting heat polewards. In fact the climate system can be regarded as an engine, with the low latitude areas being the heat source and the polar regions the heat sink.

In the summer, when the Sun is above the horizon for long periods, the polar regions receive more solar radiation than the tropics, but the highly reflective ice- and snow-covered surfaces reflect much of this radiation back to space, aided by the relatively cloud-free atmosphere that also contains little water vapour. This is one of the important feedback mechanisms operating in the polar regions where a cooling can be enhanced much more than over the unfrozen ocean or bare ground.

Large parts of the Northern Hemisphere are affected by seasonal snow cover that can respond rapidly to changes in temperature, so they are very sensitive to climatic changes. By contrast, the Antarctic continent is covered by a large ice sheet that has an extent and albedo that is relatively unchanging on the scale of decades and centuries. It is therefore the ocean areas around the Antarctic and the coastal regions of the continent that are the most sensitive to climatic variability and change on shorter timescales.

Both the atmosphere and ocean play major roles in the poleward flux of heat, with the atmosphere being responsible for 60% of the heat flux, and the ocean the remaining 40%. In the atmosphere, heat is transported by both transient eddies (depressions) and the mean flow. The depressions carry warm air poleward on their eastern sides and cold air towards lower latitudes on their western flanks. The atmosphere is able to respond relatively quickly to changes in the high or low latitude heating rates, with storm tracks and the mean flow changing on scales from days to years.

The contrasting orography of the two polar regions is very important in prescribing the atmospheric and oceanic circulations of the Northern and Southern Hemispheres. The Antarctic continent is located close to the pole, with few other major orographic features being present in the Southern Hemisphere. The mean atmospheric flow and ocean currents are therefore very zonal (east–west) in nature. For example, the Antarctic Circumpolar Current (ACC), which is one of the major oceanographic features of the Southern Ocean, can flow unrestricted around the continent, isolating the high latitude areas from more temperate mid and low latitude surface waters. This has only been the case since about 30 million years ago when the Drake Passage, which connects the South Atlantic Ocean to the South Pacific Ocean, opened up. Prior to that time the ocean currents had more of a meridional component that allowed greater penetration poleward of more temperate water masses.

The orography of the Northern Hemisphere is dominated by the major ice sheet of Greenland and the mountain ranges of the Himalayas and the Rocky Mountains. This produces a larger meridional component to the atmospheric flow than is found in the Southern Hemisphere, giving a more pronounced exchange of air masses between the Arctic and lower latitudes than occurs around Antarctica. The effects of the large land masses on the near-surface ocean currents are even more pronounced. Ocean currents, such as the Gulf Stream–North Atlantic Current system, bring warm waters to a large part of the eastern subpolar North Atlantic, and into the Nordic Seas. This current transports more warm water to higher latitudes than in any other ocean and influences the sea ice distribution in the Arctic Ocean.

The large Antarctic Ice Sheet plays a central role in determining the atmospheric circulation of the high southern latitudes. The intense surface cooling that occurs on the high Antarctic Plateau drives a persistent downslope, katabatic flow that brings cold surface air down to the coastal region. This flow plays a very important part in shaping the high latitude circulation of the Southern Hemisphere, and its influence extends into mid latitudes.

The global thermohaline circulation (THC) is the ocean system that links the major oceans of the world (Fig. 1.4). It is driven by differences in the density of sea water, which in turn is controlled by temperature and salinity. The polar regions are closely coupled to the rest of the climate system via the THC, with the system providing a direct link between the Arctic and Antarctic. The seas around the Antarctic are particularly important because of the production of AABW, which is the densest water mass found in the oceans. AABW is formed by deep winter convection in the Antarctic coastal region, particularly in the Weddell and Ross Seas. The water mass is formed as cold air from the Antarctic rapidly cools the