1 Introduction to the polar regions

1.1 Introduction

Freezing temperatures, ice, snow, continuous daylight, and long periods with no light at all. The polar regions are notorious for being frozen deserts at the ends of the Earth where nothing can survive. As this book will outline, nothing could be further from the truth. Both on the land and in the oceans of these frozen realms there is a wealth of biology that is adapted to the strong seasonality of light and temperature extremes. This extends from viruses and bacteria through to the charismatic mammals and birds that capture a wide-ranging popular interest. However, in order to understand the acclimations and adaptations of Polar biology, be it a bacterium growing on the surface of a glacier, or a phytoplankton cell encased in a frozen sea ice floe, it is essential to have an understanding of the physical forces structuring these regions.

Although the examples given in this book will point to many similarities between life in the two polar regions it is important to establish from the outset that despite being very cold the Arctic and Antarctic are very different. Much of the Arctic region is a land-locked ocean, covered by pack ice that can persist for several years. The Arctic has large areas of tundra and permafrost and several very large river systems. It contains Greenland, covered by the massive Greenland ice sheet which is on average 2 km thick. In contrast, the Antarctic is made up of a land mass almost entirely covered by the huge East and West Antarctic ice sheets (2–4 km thick) that are separated by the Transantarctic Mountains. The Antarctic continent is completely surrounded by the Southern Ocean, in which 16 million km^2 freezes over every year, effectively doubling the area of the frozen Antarctic. Whereas the Arctic has land connections with other climate zones, the Antarctic is effectively cut off from the rest of the world due to the barrier of the Southern Ocean (the shortest distance is the 810-km Drake Passage between South America and the Antarctic

Peninsula). Together the Greenland and Antarctic ice sheets account for more than 90% of the Earth's fresh water and if they were to melt sea level would increase by about 68 m (61 m from the Antarctic ice sheets and 7 m from the Greenland ice sheet).

One definition of the *polar regions* is that they are the areas contained within the *Arctic* and *Antarctic Circles*. These are parallels of latitude at 66°33′ north and south, respectively, corresponding to the angle between the axis of rotation of the Earth and the plane of its orbit around the Sun. They are the furthest latitudes from the North and South Poles where there is at least one day when the Sun does not fall below the horizon in the summer or does not rise above it in winter.

The areas encompassed by the Polar Circles total some 84 million km^2, 16.5% of the surface of the Earth. However, these circles mark no sharp transitions, either in climate or in flora and fauna, and they have little ecological significance. In places inside the Arctic Circle there are forests and thriving towns. Within the Antarctic Circle there is nothing but sea, ice, and sparse exposures of rock at the present day (Fig. 1.1). However, 60 million years ago, in the early Cenozoic, forests flourished despite Antarctic winter darkness. The polar regions are defined in various other ways by climatologists, terrestrial ecologists, marine biologists, geographers, and lawyers, but these will be considered later.

Another term that is frequently used in conjunction with polar regions is the *cryosphere* (derived from the Greek *kryos* for cold). The term collectively describes regions of the planet where water is in its solid form: it includes sea ice, lake ice, river ice, snow, glaciers, ice caps, and ice sheets, as well as frozen ground and permafrost. There is no doubt that the greatest proportion of the cryosphere is found in the polar regions, but not exclusively since high-altitude habitats clearly also store frozen water.

1.2 The energy balances of the polar regions

1.2.1 Solar irradiance

About half the solar energy entering the atmosphere consists of visible radiation; most of the rest is infrared, and a small fraction is ultraviolet. Mean values for total direct radiation from the Sun penetrating to the Earth's surface at various latitudes in the northern hemisphere are shown in Fig. 1.2. Because they have the Sun for all or most of the 24 h, polar situations actually receive more radiation around midsummar than do those on the equator. Nevertheless, the low angular height of the Sun, even in midsummer, and its disappearance in winter result in the total radiation per unit of surface area delivered during the year at the North Pole being

Fig. 1.1 Contrasting climates north and south in *summer* situations inside the Polar Circles. (a) Longyearbyen, Svalbard (78°N) in July (photograph by David N. Thomas) and (b) Scott Base (78°S) in January (photograph by Jean-Louis Tison). Note that despite the comparable time of the year that both photographs were taken, the Antarctic landscape is dominated by sea ice cover off the coast whereas the northern seas at these latitudes are ice-free (see colour plate).

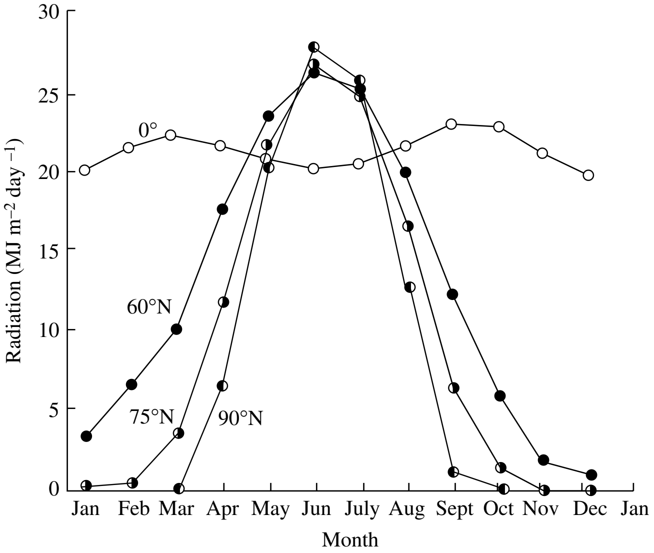

Fig. 1.2 Estimates of total direct radiation, with corrections for variations in atmospheric turbidity on the 15th day of each month at sea level at various latitudes north. From Hutchinson (1957).

less, by about 43%, than that at the equator. Direct solar radiation is augmented by scattered light from the sky to a variable extent, usually about 20% of the total. When the Sun is obscured by cloud much of its radiation is reflected back into space so that the values in Fig. 1.2, although not including scattered radiation from the sky, are likely to be overestimates.

These generalizations apply to both polar regions but there are differences: Since the Earth is closest to the Sun in the austral summer but most distant in the boreal summer, 7% more energy enters the Antarctic than the Arctic. Furthermore, the Antarctic atmosphere has less radiation-absorbing dust and pollutants, and, the continent having a higher elevation, the atmospheric mass to be penetrated by incoming radiation is less. Together, these factors result in the Antarctic getting 16% more energy. Nevertheless, the Antarctic is the colder region. The reasons for this will become apparent in the following sections.

1.2.2 Reflection and absorption of solar radiation

Incident radiation falling on a body may be reflected, transmitted, or absorbed. Absorbed radiation is changed into thermal energy in the absorbing material. The ratio of reflected to incident radiation is known as the *albedo* and has the value of 1.0 for complete reflection and of 0.0 for complete absorption. Snow and ice have high albedos, water a low albedo, and rocks

Fig. 1.3 Snow-covered ice shelf and sea ice with high albedo compared with open water with low albedo (photograph by David N. Thomas).

Table 1.1 Albedos of various natural surfaces

Surface	Albedo
Snow-covered sea ice	0.95
Fresh snow	0.8–0.85
Melting snow	0.3–0.65
Quartz sand	0.35
Granite	0.15
Bare earth	0.02–0.18
Coniferous forest	0.10–0.14
Water	0.02
The Earth as a whole	0.43

are intermediate (Perovich *et al.* 2002; Fig. 1.3 and Table 1.1). The mean albedos of the polar regions vary seasonally but are always higher than that of the Earth as a whole. That of the Arctic is lower than that of the Antarctic, 0.65 compared with 0.90, as a result of loss of reflective snow cover and relatively greater ice melt in summer. In the Arctic ice covers about 2 million km^2 of land and sea ice extends over 7 million km^2 at its minimum and 14–16 million km^2 at its maximum in late February or March. In the Antarctic, land ice extends over 12.6 million km^2 and sea ice over 4 million km^2 at its minimum, increasing to about 20 million km^2 at

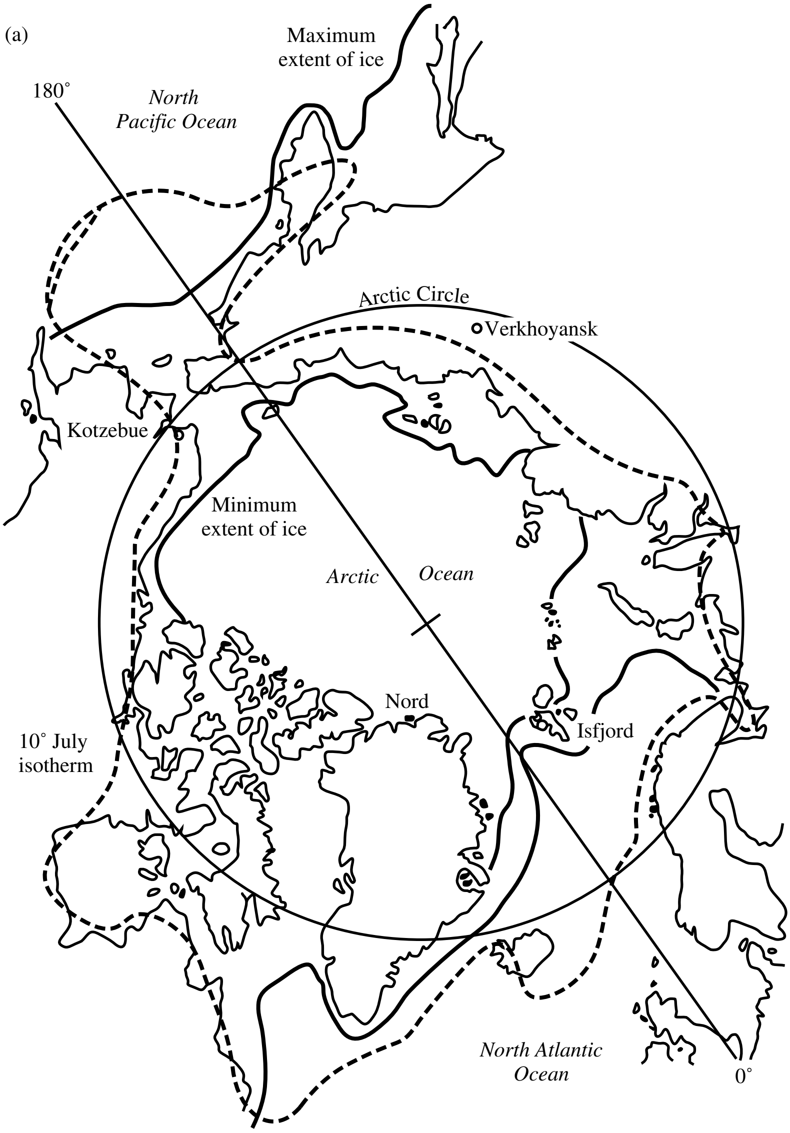

Fig. 1.4 (Continued)

its maximum in September, when it goes well north of the Antarctic Circle all round the continent and effectively more than doubling its size (Fig. 1.4). The total area of high albedo in the summer is sufficient at both poles to reflect much of the incident radiation back into space and thus reduce heating of land and sea. This resolves the paradox that the area which receives the maximum monthly input of solar energy of any on Earth, the ice sheet of East Antarctica, is also the coldest on Earth.

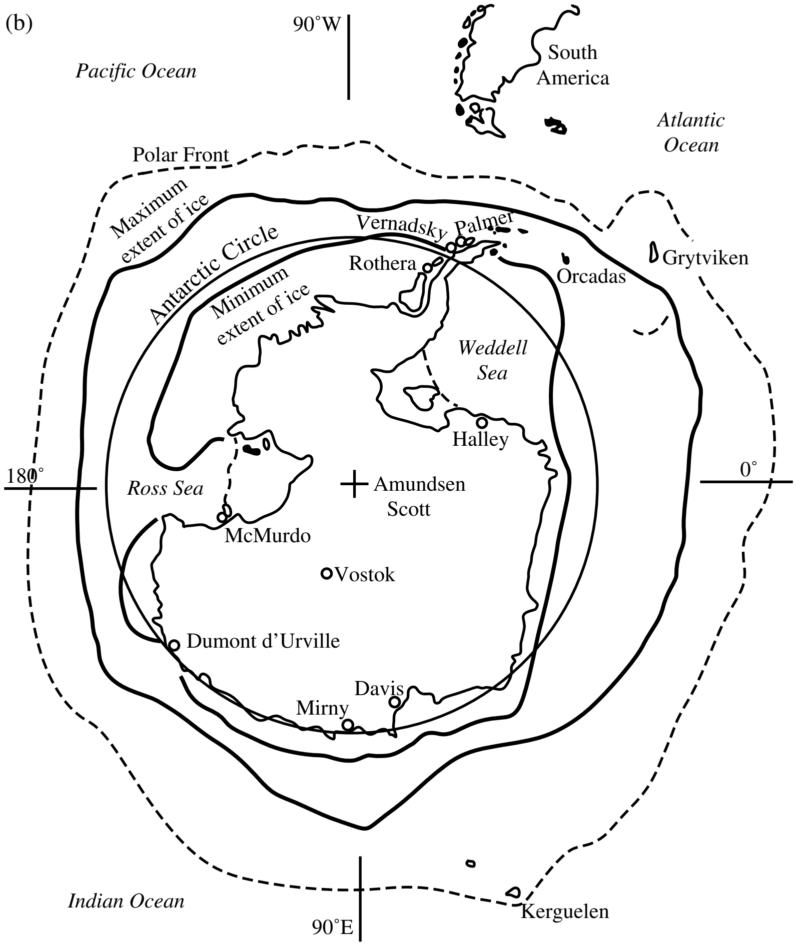

Fig. 1.4 Extents of sea ice and positions of Polar circles in the (a) Arctic and (b) Antarctic. The weather stations indicated are the same that appear in Fig. 1.5.

Spots of low albedo within polar regions can absorb large amounts of heat. The Russian station, Mirny (66°33′S 93°01′E), is on snow-covered ground whereas the nearby Oazis station (66°30′S 101°E) has bare rock around it. At Mirny, most of the incoming radiation is reflected and little heat is accumulated in the ground even at midsummer; because of its high albedo, snow cover tends to persist once established. At Oazis, the rock surface heats up in summer and soil temperatures rise to 10°C or so above that of the ambient air. A water surface, which also has a low albedo except at low angles of incidence, behaves similarly. Since water has a high specific heat, lakes and seas act as particularly effective heat stores. Not only does water transmit radiation into its depths but heat can be carried downwards by its turbulence. Were it not for extensive and persistent high-albedo snow cover, Polar climates could be temperate, as, indeed, they have been in the past.

1.2.3 Long-wave radiation from terrestrial sources and its absorption in the atmosphere

Thermal energy acquired by absorption of solar radiation is lost by emission of radiation of a longer wavelength, infrared radiation. The amount of energy re-radiated is a function of the infrared emission characteristics of the surface and the fourth power of its absolute temperature. Most natural surfaces have emission characteristics in the same range: snow, ice, rock, and water all having similar high values at the same temperature. The Earth's surface, to a good approximation, can be regarded as having perfect infrared emissivity at a temperature of 285 K in the waveband 4.5–50 μm, with a peak at about 10 μm.

Whereas the atmosphere is highly transparent to solar radiation it absorbs terrestrial radiation because of the presence of clouds, water vapour, and certain gases, all of which show high absorption within the waveband just specified. These gases, which include carbon dioxide and methane, have achieved notoriety as so-called greenhouse gases because of their increasing concentrations in the atmosphere, leading to increasing interception of infrared radiation, resulting in global climate warming. Without the blanketing effect of the atmosphere the Earth's surface temperature would be 30–40°C lower than it is and would vary between greater extremes of heat and cold. Just now the blanket is becoming oppressively thick (see Chapter 10).

Liquid water in the form of clouds is nearly opaque to terrestrial radiation even though its concentration may be only $1\,\mathrm{g\,m^{-3}}$, equivalent to a thickness of $0.001\,\mathrm{mm\,m^{-1}}$. Clouds of ice or snow are similarly highly absorbing. Water vapour present in the clear atmosphere also has high absorption for most wavelengths in the terrestrial emission spectrum but has a window in the region of 10 μm, the region of maximum terrestrial emission. The frost which often accompanies a cloud-less night is a familiar example of the heat loss that this allows.

1.2.4 Long-wave radiation emission in the atmosphere

The absorbing agents in the atmosphere heat up and in their turn emit long-wave radiation according to their temperature and emission characteristics (Law and Stohl 2007). Some of this, about 75%, will return to the Earth's surface and there be reabsorbed. The net loss of energy from this surface will thus be the radiation which it emits itself less that of the back radiation received from above. When a layer of warm cloud overlies cold ground the balance becomes positive. The rest of the long-wave radiation emitted by atmospheric components escapes into space. There is an overall heat loss via long-wave radiation from the Earth and its atmosphere because their temperatures are higher than that in space.

Net heat loss is greater in the Antarctic than in the Arctic. The reason for this lies partly in the greater prevalence of clouds in the Arctic, particularly at its periphery, as compared with the Antarctic, the high continental plateau of which is generally cloud-free. Furthermore, the atmosphere over the plateau is more transparent to long-wave radiation because of its thinness and dryness. An added complication in both polar regions is that of temperature inversions, that is to say increases, rather than decreases as normally found, of temperature with height above ground. These arise as a result of snow surfaces beneath clear skies reflecting nearly all incoming radiation, so that air near the surface becomes chilled and dense. Above it, between 200 and 1000 m, is less-dense air containing more moisture which intercepts some outgoing long-wave radiation and remains warmer. Inversions are prevalent over the Antarctic plateau for most of the year and account for the fact that temperatures on the plateau, after a rapid fall in autumn, scarcely decrease thereafter so that the winter is *coreless* (Fig. 1.5). Variations in refraction associated with inversions produce the optical phenomena, such as mirages, which are characteristic of polar regions (Pielou 1994).

1.2.5 Transport and global balance of thermal energy

Around the poles there is net loss of energy by radiation over the year whereas in equatorial latitudes there is a net gain. Losses balance gains and as a whole the Earth and its atmosphere neither warm up nor cool down. The loss of heat from the polar regions is made good by a flow of excess heat carried in currents of air or water from lower latitudes. The poles are sinks for thermal energy and the equatorial regions the source. Air transports not only sensible heat but also latent heat in the water vapour it contains. Some is released when the vapour condenses to form clouds (539 cal g^{-1}) and some more when the liquid water freezes (79.8 cal g^{-1}).

If Ptolemy's geocentric theory were correct and the Earth remained motionless while the Sun went around it, warm air carrying water vapour with it would rise in equatorial regions and flow towards each pole along meridional paths. Cooling on the way, this air would eventually sink and return towards the equator, again along meridional tracks, at a lower level. In the oceans, sea water, concentrated by evaporation in low latitudes, would become saltier, more dense, and sink, likewise flowing polewards and carrying heat along meridional pathways, assuming no obstruction by land masses. In high latitudes it would rise as it encountered water which, although less salty, would be denser because it was colder. However, because the Earth rotates, flows of air and water are deflected, by the Coriolis

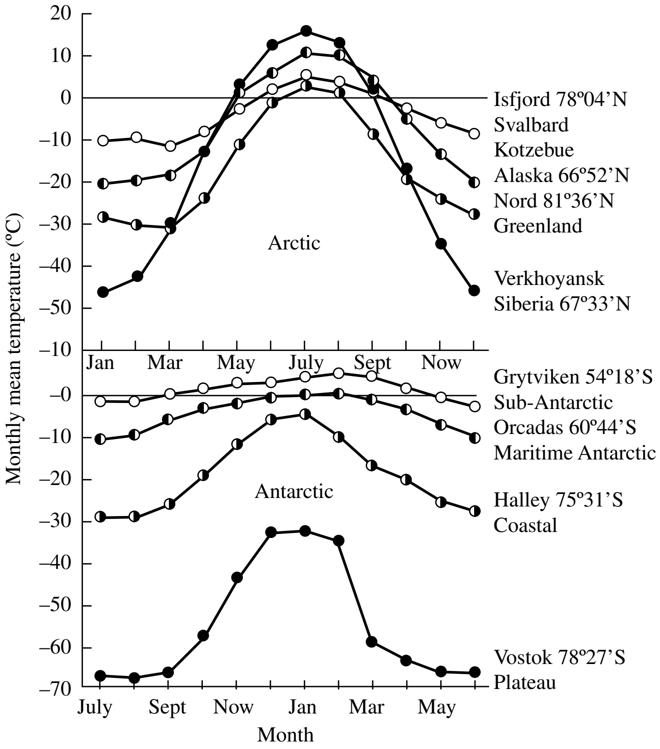

Fig. 1.5 Mean monthly temperature at different locations (see Fig. 1.4) in the Arctic and Antarctic. N. B. at Vostok the temperature from April to September remains more or less level — the winter is *coreless*, unlike that in the Arctic, which has a sharp minimum. Data from Stonehouse (1989).

force, to the right of the direction of movement in the northern, and to the left in the southern hemisphere. The Coriolis force is zero at the equator and maximal at the poles.

In the atmosphere, thermal energy is mostly transported in the lower layer, the *troposphere*, which is about 10 km thick and separated by a temperature minimum, the *tropopause*, from the *stratosphere*. The basically meridional two-way traffic of warm air polewards and cool air equatorwards is obscured, not only by the Earth's rotatiffon, but also by the different thermal effects of continents and oceans. The result is a complex pattern of zonal and cellular circulation. Salient features are that, between latitudes 30 and 60°, both north and south, there are zones of predominantly low pressure and westerly winds, and polewards of 60° there are zones of high pressure with north-easterly and south-easterly winds, respectively, north and south.

Water currents are also subject to the Coriolis force but are obstructed and deflected by land masses and irregularities in the seabed. A further complication is that atmosphere and ocean interact. The drag of winds on the sea surface induces currents and, also, by setting up slopes in the surface, winds produce other currents in response to the pressure gradients that arise. Wind-induced currents may be temporary, varying with local weather, but the major oceanic circulations correspond roughly to the pattern of the prevailing winds. Such currents are largely superficial, and, for present purposes, deep-water currents, the direction of which need show no relation to those at the surface, are more important. The temperature at great depths in the oceans is everywhere near to freezing point. This cold bottom water comes from two main sources, one in the Greenland Sea, the other in the Weddell Sea in the Antarctic, where surface water becomes cold and dense enough to sink to the bottom and flow equatorwards. Other deep-water currents carry warm salty water from equatorial regions polewards in replacement. These currents are of enormous volume but move slowly, perhaps around 1 or 2 km per month, and so the water in them stays below the surface for many hundreds of years.

1.2.6 Heat influx and balance in the polar regions

Against this general background we can look more specifically at the paths by which thermal energy reaches the polar regions. First, a radical geographic difference between Arctic and Antarctic is of key importance. Whereas the Arctic centres on a sea of some 14 million km^2 enclosed by islands and the northern stretches of continents, the other is a continent of 13.3 million km^2—larger than Europe but smaller than South America—surrounded by a belt of ocean which separates it by 800 km from an outlier of the nearest major land mass (Fig. 1.6). This difference has profound consequences for their respective climates, biology, and importance in the regulation of the global environment (Walton 1987).

1.2.7 The Arctic

The major input of heat is provided by northward-moving warm air which interchanges with cold polar air in cyclones associated with low pressure along the atmospheric Polar Front in the region of 60°N. Variations in surface topography introduce complications and a regular succession of cyclones is frequently obstructed by well-developed stationary regions of high pressure: so-called anticyclonic blocking. From there, the warm air travels high in the troposphere to subside around the pole. It then returns as surface winds away from the pole, the Coriolis force giving these an easterly direction. This is an anticyclonic situation. Over the sea ice of the Arctic Ocean the motion of these winds is imparted by pressure differences. On the Greenland ice cap, winds become related to topography, dense cold air flowing downslope. Such *katabatic* winds are intermittent. The air accelerates as it

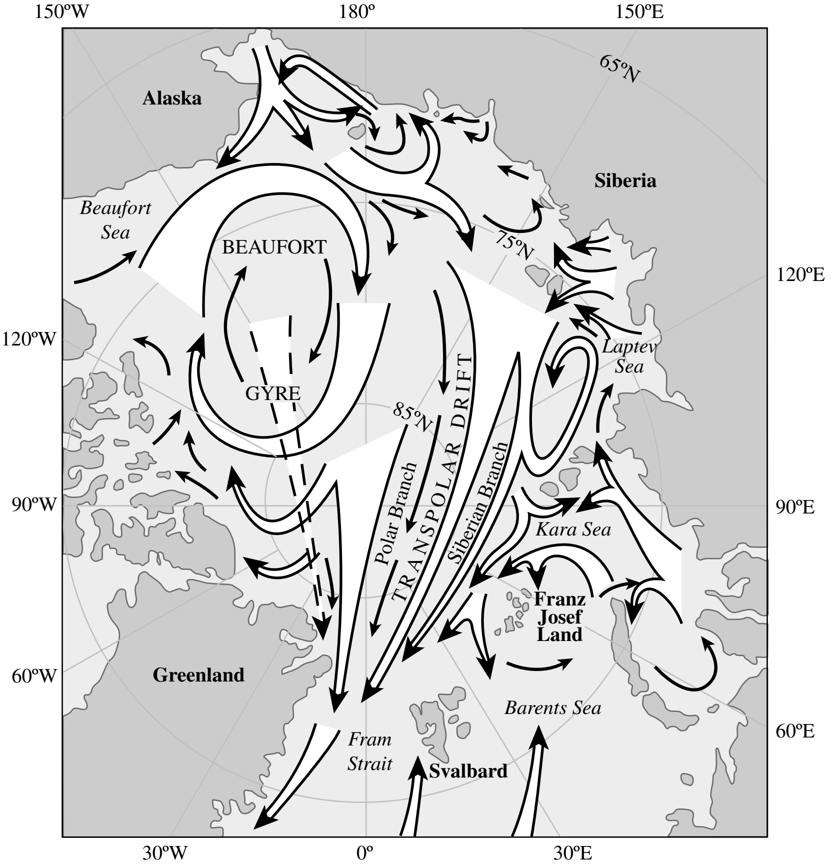

Fig. 1.6 Principal surface water currents of the Arctic Ocean and seas. From Wadhams (2000).

descends, becoming compressed by the higher pressure at the lower levels and developing heat equivalent to the work done.

Heat is also contributed by the great Siberian rivers (Fig. 1.7), which introduce fresh water at a rate of about 3500 km^3 year^{-1}, mainly in summer when its temperature may get up to between 10 and 15°C. An additional 1500–2000 km^3 year^{-1} enters as a freshwater fraction of the Bering Strait inflow. The main ocean current flowing into the Arctic Ocean (Carmack in Smith 1990) is the West Spitsbergen Current, a northward-flowing extension of the Norwegian Atlantic Current, passing through the Fram Strait (approximately 80°N 0°; Fig. 1.6). This follows a deep trench leading to the Arctic Ocean. The access via the Barents Sea is partially obstructed by shallows. The water in this current is warm (above 3°C) and relatively saline (salinity[*] greater than 34.9). The amount of water transported is uncertain: estimates

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[*] Salinity is defined as the grams of salt dissolved per kilogram of water. There are no units.

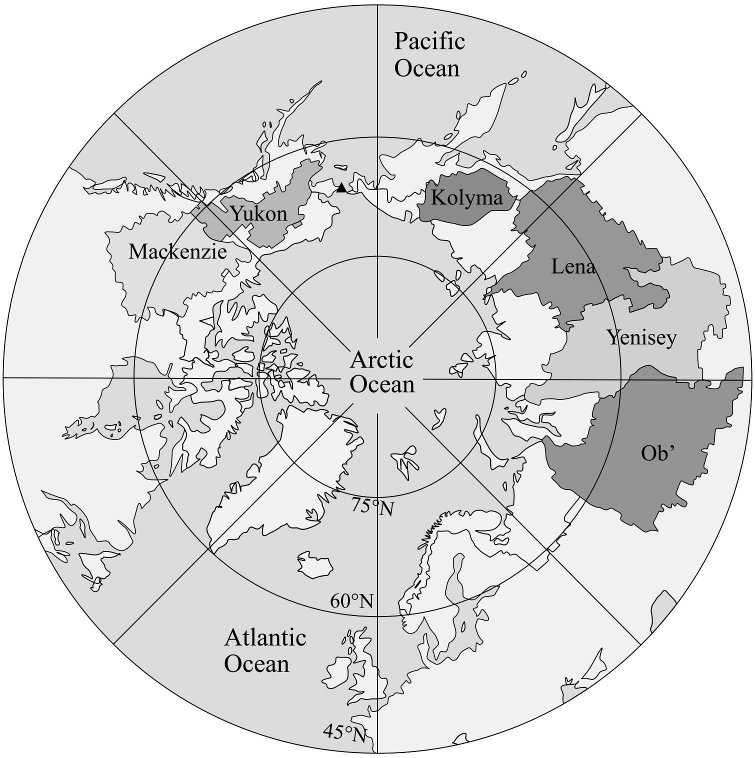

Fig. 1.7 Map showing major river catchments discharging into the Arctic Ocean (image courtesy of R.M. Holmes).

vary between 2 and 8 Sv (1 Sv or Severdrup = $10^6\,m^3\,s^{-1}$), or 60 000 and 250 000 $km^3\,year^{-1}$, but it is possible that as much as half of this circulates in the vicinity of the Fram Strait without entering the Arctic Ocean.

Alongside the West Spitsbergen Current to the west is the East Greenland Current. This is the main current out of the Arctic Ocean and carries cold (below 0°C), relatively fresh (less than 34.4 salinity), water southwards. The flow of this current is between 3 and 30 Sv (91 000–910 000 $km^3\,year^{-1}$) and it carries with it some 4 million MT of drift ice to lower latitudes. The Bering Strait is narrow (85 km) and shallow (50 m), allowing a small (about 0.8 Sv or 25 000 $km^3\,yr^{-1}$) northerly flow. Within the Arctic Ocean the Transpolar Drift, a surface current, flows from the Siberian to the Greenland side, where it feeds into the East Greenland Current. It was trusted by Nansen to carry his ship, the *Fram*, beset in the ice, across the Arctic Ocean into the vicinity of the North Pole. A less heroic demonstration of the Transpolar Drift is being provided by a consignment of 29 000 plastic floating bath toys including ducks, frogs, and turtles, lost from a container ship in the North Pacific at 44°N 178°E in October 1992. It was proposed that the floating toys would be transported by the pack ice across the Arctic Ocean into the North Atlantic. To the delight of oceanographers tracking these toys in 2003, they showed up on North Atlantic coastlines and findings are still being reported in July 2007.

The pack ice, up to 12 m thick, plays an important part in conserving heat. The sea water itself, with a mean depth of about 1200 m and a volume of about 17 million km^3, provides an immense heat reservoir. Its ice cover reduces heat transfer to the atmosphere by one or two orders of magnitude compared with that from open water. Furthermore, largely because of the inflow of river and Bering Strait waters, a layer of low salinity water floats on top of the denser water in the Arctic basin, producing a marked *halocline* at between 30 and 60 m which limits the convection that would otherwise mix the whole water column and promote heat loss. The deep water consequently remains between −0.5 and −0.9°C, appreciably above its freezing point of –2.0°C. These various factors contribute to the generally higher temperatures of the Arctic compared with the Antarctic. Plans to divert the southward part of the flow of some Siberian rivers to alleviate water shortages in the south perhaps need not create too much alarm. On present evidence it seems unlikely that such diversions would have major effects on circulation or sea ice distribution in the Arctic Ocean.

1.2.8 The Antarctic

Although the heat exchanges of Antarctica are still incompletely understood, it presents a simpler situation for analysis, having an approximately circular ice-covered land mass forming a dome, without too many topographical irregularities, nearly centred on the geographical pole and surrounded by a continuous belt of deep ocean (Walton 1987). This allows the collection of meaningful data and the construction of realistic mathematical models of circulatory processes.

The chief agent of imput of thermal energy is again atmospheric circulation. The zone of westerly winds produces a succession of cyclones which satellite images show as a regular procession of cloud spirals around the continent at latitudes 60–65°S. The Antarctic thus contrasts with the Arctic in that anticyclonic blocking is infrequent. The cyclones often swing south into the Ross Sea area but rarely depart from their circumpolar track to carry warm air into the centre of the continent. As in the Arctic, cyclones provide a mechanism for exchanging cold polar air for warm moist air from lower latitudes. The water vapour is again a source of thermal energy. This air travels south at an intermediate height in the troposphere and sinks in the high-pressure region over the summit of the polar plateau. The ice dome favours the initiation of katabatic winds, which under the influence of the Coriolis force follow a north-westerly track. This layered system of air movements is seen in dramatic form when smoke from the volcano Erebus (3785 m, 77°40′S 167°20′E) is carried polewards whereas at sea level a blizzard may be blowing from the south. If these low-level winds are sufficiently strong, surface irregularities such as wind-produced ridges in the snow (*sastrugi*) cause turbulence which disturbs inversions and mixes in warmer air and moisture from above. The speed of katabatic winds increases with slope and so turbulent heat exchange is about four times greater around the edge of the continent than it is in the interior.

There are no permanent rivers to contribute to the heat budget of the Antarctic. In the sea (Carmack in Smith 1990) there is meridional transport which is, however, deflected by the wind-driven Antarctic Circumpolar Current. This current, being deep-reaching and confined only at the Drake Passage and south of the Australasian land mass, where it has to pass through a deep channel connecting the Indian and Pacific Oceans, is an enormous flow of about 130 Sv (4 million km^3 $year^{-1}$). This is no mean barrier to meridional transport and is regarded as one of the major factors contributing to the exceptionally frigid state of the Antarctic. Nevertheless, considerable southward transport of heat, mainly from the Indian Ocean, takes

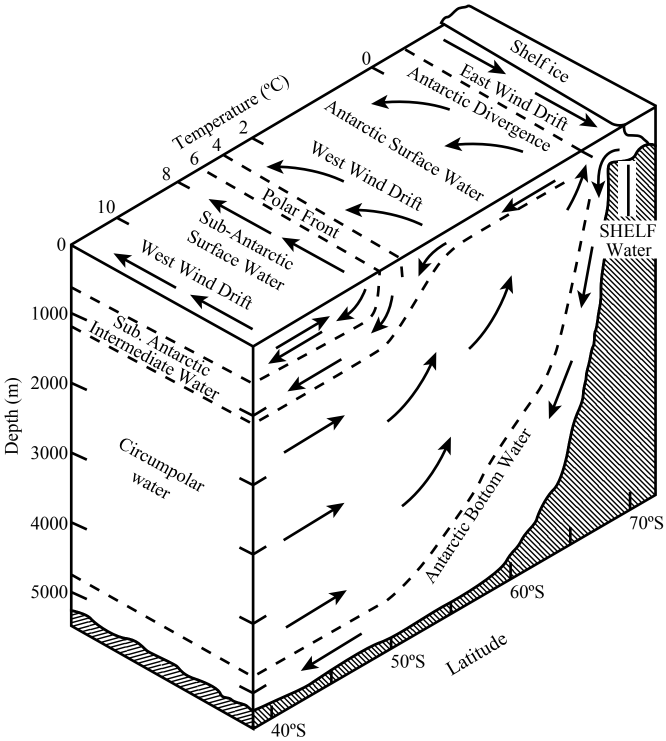

Fig. 1.8 Three-dimensional diagram showing the circulation patterns and water masses in the Southern Ocean.

place in the Circumpolar Deep Water (Fig. 1.8), which has temperatures between 0 and 1.8°C and maximum salinity of around 34.76. This wells to the surface at the Antarctic Divergence, about 70°S, and spreads north and south. The north-flowing fraction mixes with fresh water released by ice melt, giving temperatures of around −0.4°C and salinities of about 34.20. It forms a layer, some 200 m in depth, separated by a sharp density gradient (*pycnocline*) from the Circumpolar Deep Water. Meeting warmer Subantarctic Surface Water, it plunges beneath this at the Antarctic Polar Front, a feature also known by the not-quite-synonymous name of Antarctic Convergence (Fig. 1.8). The Polar Front remains in a surprisingly constant position, extending all the way round the continent within the Circumpolar Current (see Fig. 1.4b). It is a boundary of great biogeographical importance and is easily detected by abrupt changes in temperature in both surface sea water and air. The upwelling water from the Circumpolar Deep Water which continues on south becomes colder and mixes with water, from the continental ice shelves, charged with brine formed by freezing of sea water. Being both cold (0.4–1.3°C) and saline (salinity of 34.66–34.72) it sinks and then spreads northwards across the sea bottom (Jacobs 2004). The Weddell Sea and to a lesser extent the Ross Sea are the major centres for the production of this Antarctic Bottom Water. Traces of it have been found as far beyond the equator as 17°N in the Atlantic Ocean. The scale of events in the Weddell Sea is shown by the estimate of between 76 and 97 Sv (2.4–3.0 million $km^3 year^{-1}$) for water transport in the gyre occupying its basin. This vastly exceeds that in Arctic waters.

The area of the Southern Ocean covered by sea ice increases five- or six-fold each winter (Fig. 1.4b) but with great year-to-year variation in timing, extent, and distribution. This interannual variability is linked to atmospheric processes and the flow rates and directions of ocean currents (Murphy *et al.* 1995). Unlike Arctic ice, which is constrained by land, Antarctic ice is free to spread over deep ocean, almost anywhere that wind and tide take it. The heat exchanges of the Southern Ocean are modified correspondingly. Ice formation is most active in coastal regions subject to cold katabatic winds: further offshore turbulence retards ice formation. Both pack ice and icebergs are carried in a generally northern direction and, since freezing involves release of latent heat, whereas the eventual melting requires supply of heat, this implies a net poleward transport of heat against an export of fresh water. The release of heat by freezing at the beginning of winter and its uptake on melting in summer work to buffer temperatures. The high albedo and insulating properties of the ice also minimize heat exchanges.

The Arctic and Antarctic are the two great heat sinks which between them determine the patterns of both atmospheric and oceanic circulations and are thus key areas in regulating the global environment. Of the two, the Antarctic is the dominant.

1.3 Climate

1.3.1 The climatic boundaries of the polar regions

Another simple definition of the polar regions is that they are those areas in the vicinity of the poles, where the mean temperature of the warmest month is less than 10°C. The 10°C summer isotherm (Fig. 1.4a) usually coincides with the limits of tree growth (Aleksandrova 1980). Isolines of radiation balance give a better match to tree line, although they sometimes deviate by as much as 160 km. The position of the tree line depends on both latitude and altitude. The transition from tall forest to dwarf, shrubby, vegetation, which marks the tree line, is sometimes strikingly sharp, largely because single exposed trees, not being able to ameliorate their environment, tend to be eliminated. A closed canopy affords some protection from wind stress but since forest vegetation is penetrated by large-scale eddies temperatures of the above-ground tissues are closely coupled to those in the air. In contrast, shrubby vegetation is aerodynamically smoother and dissipates heat less readily, experiencing tissue temperatures and microclimates that, on average, are warmer than the air. Consequently, dwarf shrubs can succeed in polar climates in which trees fail to grow and reproduce.

In the Arctic the 10°C summer isotherm undulates around the Polar Circle, going well south of it in the regions of the Bering Strait and the north-west Atlantic where the Kamchatka and Labrador Currents, respectively, bring cold surface water down from the north. The isotherm goes north along the coast of Norway because of the warm North Atlantic Drift (Fig. 1.6). Around the Antarctic the 10°C summer isotherm runs well north of the Polar Circle, at about 50°S, and almost entirely over ocean, only touching land at the tip of South America. There the coast is mostly forested. The sub-Antarctic islands south of the isotherm have vegetation which resembles Arctic tundra and are treeless. The Falkland Islands (approximately 53°S 58°W) lie just on the cold side of the isotherm and have no native trees but their grasslands, dwarf shrub heaths, and *fell fields* (with discontinuous cover of cushion plants) are scarcely sub-Antarctic in character and will not be dealt with here.

1.3.2 The Arctic climates

Within the confines of the 10°C summer isotherm conditions are generally cold, dry, and windy (Sugden 1982, Stonehouse 1989) but there are variations which are not easy to classify. The Arctic can be divided into the central maritime basin and the areas peripheral to it, in which can be distinguished the ice caps, polar maritime climates (located principally around the Atlantic and Pacific coastlines), and the polar continental climates as in north Alaska, Canada, and Siberia. There are no fixed meteorological stations in the central maritime basin but observations have been made from a succession of stations on drifting ice islands. This is a climatically stable area with a strong central anticyclone, clear skies, and light centrifugal winds during the winter. Because of the reservoir of heat in the ocean, temperatures do not fall to extremely low levels, averaging –30°C offshore and –26 to –28°C in the coastal regions during the depth of winter. When the Sun returns the anticyclone weakens and there are incursions of depressions, bringing moist air, fog, cloud, snow, rain, and strengthening winds. Temperatures, except in a small central area, rise above freezing point so that the periphery of the pack ice melts and large areas of open water appear along the Alaskan and Eurasian coasts during June and July.

There are ice caps on the more northerly islands, for example, about 58% of Svalbard (approximately 79°N 15°E) is permanently ice-covered. That on Greenland, which covers most of the island and rises to 3000 m, is by far the most massive. It is fed by snow borne by year-round south-western airstreams, which deposit some 100 cm rain equivalents annually in the south but only about 20 cm in the north, parts of which are consequently almost ice-free. Temperatures on the plateau of the ice cap fall to −40 to −45°C in winter, rising to –12°C in summer.

Arctic continental climates are dominated by anticyclonic conditions in winter with low temperatures, light winds, and little precipitation. Mean monthly temperatures rise to freezing point around May and can get well above it in the short summer (Fig. 1.5). Weakening of the anticyclone allows incursions of depressions, bringing warm, moist, oceanic air with precipitation that favours the development of tundra on low ground and ice caps and glaciers higher up. The most extreme continental conditions are found around Verkhoyansk (67°33′N 133°25′E), the 'pole of cold', in eastern Siberia, where an intense winter anticyclone spreads cold, dry, air in all directions. Being well away from the sea it has variations in temperature from −67.8°C in winter to 36°C in summer (Fig. 1.5). Precipitation is mainly in the form of summer rain and amounts to only 15 cm per annum.

Maritime climates are ameliorated by the sea, especially where there are warm currents. In the Canadian Arctic, the worst climate is encountered in the Hudson Strait area (approximately 63°N 70°W), which is dominated by open water and frequent cyclonic activity, giving the highest average temperature, but the heaviest snowfall, highest average wind speeds, and greatest number of summer fogs in this sector. This is the region in which many of the early seekers after the Northwest Passage came to grief. The south-west of Greenland is warmed by an offshoot of the North Atlantic Drift (see Fig. 1.5) and is comparatively free of sea ice. Its mild climate allows sheep farming on luxuriant tundra within a short distance of the ice cap. Parts of Iceland likewise have a mild climate and forests of birch and spruce in the south. Its northern shores have pack ice drifted in by the East Greenland Current. The same current keeps the east coast of Greenland cold, even in summer.

The North Atlantic Drift passes Iceland to give Svalbard (Fig. 1.5) and the north-western tip of Europe remarkably temperate climates with the tree line going far north. Only the northern part of Svalbard remains ice-bound in summer. The effect of the same current persists along the Eurasian coast of the Arctic Ocean as far east as Novaya Zemlaya (approximately 75°N 60°E), keeping the Barents Sea open in summer. Depressions bring abundant summer rain as well as winter snow. The great Siberian rivers have some ameliorating influence but further east still the coastal climate becomes harsher with short, cold, summers and frigid winters. Precipitation decreases and Kotel'niy (75°59′N 138°00′E) on Ostrova Novosibirskiy, which has only 13 cm per year, can be described as desert.

1.3.3 The Antarctic climates

The array of Antarctic climates is simpler (Sugden 1982, Stonehouse 1989). The central feature here is the enormous, high, continental plateau, usually dominated by a high-pressure system. With its 'coreless' winter goes a 'pointed' summer, lasting only a few weeks (Fig. 1.5). When planning their attempts on the South Pole, neither Amundsen nor Scott had any idea of this state of affairs. Amundsen was lucky to arrive just before the peak of summer and Scott desperately unlucky to arrive just after it. Temperatures depend on altitude as well as latitude and the Russian base Vostok at 78°28′S and 3400 m above sea level holds the world record for low temperature, –89.5°C (Fig. 1.5). Wind speeds are generally low and precipitation extremely low. Direct measurement of snowfall is imprecise at best and the prevalence of drift on the continent makes it difficult or impossible. Between 3 and 7 cm rain equivalents seems to be likely—less than in most tropical deserts—but it is the extremely low moisture content of the air which makes the Antarctic plateau so highly desiccating.

As the slope of the ice cap steepens towards the coast, a different type of climate predominates, with strong and persistent katabatic winds averaging around 11 m s^{-1} (39 km h^{-1}) and occasionally reaching 300 km h^{-1} (Fig. 1.9). The coast itself has milder temperatures, dropping to around –20°C in winter and rising to near zero in summer (Fig. 1.5). Over the sea the cold air from katabatic winds rises and is dissipated in turbulence, leaving conditions at the surface more tranquil. Cyclonic activity sometimes penetrates landwards, bringing strong winds and precipitation. The weather is very dependent on topography, which affects the incidence of katabatic winds and the amount of sea ice insulating the coast from the relatively warm

Fig. 1.9 Leaning on the wind while collecting ice for the kitchen, Adelie Land, Antarctica. From the original lantern slide taken by Frank Hurley taken during the Australasian Antarctic Expedition between 1911 and 1914. Courtesy of the Scott Polar Research Institute.

sea. The US station, McMurdo, at 78°S on the Ross Sea has persistent sea ice but sunny summers with little snow so that the rocks are exposed for 3 or 4 months each year. The effect of topography is particularly marked on the Antarctic Peninsula. On its west coast the Ukrainian station, Vernadsky (previously the British station, Faraday, at 65°15′S 64°15′W) has a mild maritime climate. At the same latitude on its east coast frigid conditions are maintained year round by cold water brought from higher latitudes by the Weddell gyre and an ice shelf extends out from the shore. Temperatures are some 4–6°C colder than on the west coast.

Topography also produces oases, or dry valleys, which are a special feature of Antarctica. These are ice- and snow-free areas are found at various points around the continent. The dry valleys of Victoria Land, accessible from McMurdo Station, have been investigated intensively, as have those of the Bunger Hills in the vicinity of Mirny. Dry valleys (Fig. 1.10; see also Chapters 3 and 5) exist where loss of snow and ice by *ablation* (i.e. removal by sublimation or run-off of melt water) exceeds addition by precipitation and movement of ice into the area. The configuration of the land surface must be such as to divert the flow of ice elsewhere and also to provide a precipitation shadow. The effect on the radiation balance of the resulting lowering of albedo has been mentioned and temperature fluctuations from around −38°C to as much as +15.6°C have been recorded. Winds are generally light but strong katabatic winds blow occasionally and wind-eroded rocks, *ventifacts*, are a striking feature of the dry valleys. The bare area tends to extend along the direction of the prevailing wind since debris is carried downwind and, being deposited on snow, decreases its albedo,

Fig. 1.10 Aerial view of Lake Fryxell in the McMurdo Dry Valleys, Antarctica (photograph by Dale Anderson) (see colour plate).

promoting melting and exposure of bedrock. Extreme desiccation is a major factor for living organisms; the mummified remains of the occasional seals and penguins which stray into these cold deserts may remain for centuries. The annual precipitation is around 4.5 cm rain equivalents.

The maritime Antarctic, taken as the zone from 70°S northwards to 55°S, including the Antarctic Peninsula and its associated islands together with adjacent archipelagos, falls in the domain of cyclones. Vernadsky Station has mean temperatures of around –10°C in the winter rising to near zero in summer. There is more cloud than on the coasts of the main continent and winds are stronger. Sea ice usually disperses in early spring and reforms in autumn. Signy Island (60°43′S 45°36′W), in the South Orkney, has much the same sea ice conditions and temperature range but has cloud for 80% of the summer and 60–80% of the winter. Annual precipitation, mostly snow but sometimes rain, amounts to 40 cm rain equivalents.

All these islands are well south of the Polar Front. Those in the vicinity of the front are termed *sub-Antarctic*. South Georgia (approximately 54°30′S 37°00′W) is some 350 km south of the front. It has sub-zero temperatures every month of the year (Fig. 1.5) and permanent ice fields, although temperatures of 15°C are not uncommon. It receives an almost continuous series of atmospheric depressions and its climate may be summed up as generally cold, wet, and cloudy, with strong winds, subject to abrupt change but without great seasonal variation. Katabatic winds, caused by cold air spilling down valleys, give rise to sudden squalls and whirlwinds, known as williwaws, which are frequent in some of the harbours. The south-west coast, exposed to the prevailing westerly winds, has a more rigorous climate than the sheltered north-east. These winds, heavily laden with water vapour, are forced to rise over the steep 3000-m spine of the island and in doing so expand, cool, and deposit their moisture as rain or snow. The then relatively dry air descending on the leeward side of the mountains is compressed and so warms up, producing rises in temperature of as much as 10°C. These *Föhn* winds are an outstanding feature of South Georgia. Icebergs are common about its coasts but pack ice reaches it rarely. The French archipelago of Kerguelen (approximately 49°S 70°E) is about as far south as Paris is north, but its situation just on the Polar Front ensures a sub-Antarctic climate similar to that of South Georgia. Temperatures are again rather uniform, only falling a little below freezing in winter and rising little above 10°C in summer but at 1050 m it has an ice cap giving rise to numerous glaciers. Like South Georgia it has strong westerly winds, fogs, rain, and snow. Icebergs are occasionally seen but its coastal waters are always free of ice.

1.4 Thermohaline circulation

Despite their very different characterstics and the vast expanses covered by the oceans of the world, they are all interconnected by a large-scale movement of water that is referred to as the meridional overturning circulation (MOC), or *global thermohaline circulation* or *global ocean conveyor belt* (Broecker, 1997, Broecker *et al.* 1999, Clark *et al.* 2002; Fig 1.11). The basis of

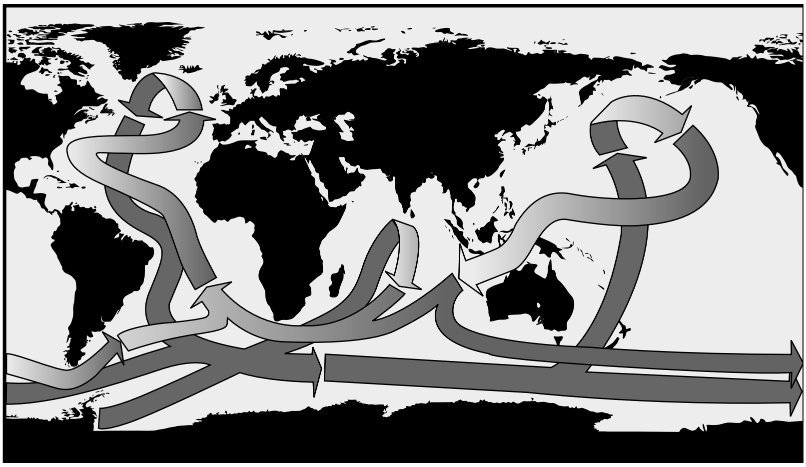

Fig. 1.11 Illustration of the global thermohaline circulation or meridional overturning circulation (MOC) (sometimes referred to as the *global ocean conveyor belt*).

themohaline circulation is that a kilogram of water that sinks from the surface into a deeper part of the ocean displaces a kilogram of water from the deeper waters. As sea water freezes in the Arctic and Antarctic and ice sheets consolidate, cold, highly saline brines are expelled from the growing ice sheet (see Chapter 7) increasing the density of the water and making it sink.

In the conveyor-belt circulation, warm surface and intermediate waters (0–1000 m) are transported towards the northern North Atlantic, where they are cooled and sink to form North Atlantic Deep Water that then flows southwards. In southern latitudes rapid freezing of sea water during ice formation also produces cold high-density water that sinks down the continental slope of Antarctica to form Antarctic Bottom Water. These deep-water masses move into the South Indian and Pacific Oceans where they raise towards the surface. The return leg of the conveyor belt begins with surface waters from the north-eastern Pacific Ocean flowing into the Indian Ocean and then into the Atlantic Ocean.

It is not just the temperature and salinity of the deep-water formation in the polar regions that is crucial to the ocean circulation. These water masses are rich in oxygen, and so are fundamental for transporting oxygen to the ocean depths where respiration by deep-sea organisms consumes oxygen. The transport of dissolved organic matter and inorganic nutrients is also governed fundamentally by this transport, increasing the nutrients being remineralized during the transfer of the deep-water masses. Therefore water rising at the end of the conveyor belt in the north-eastern Pacific has higher nutrient loading, and lower oxygen concentrations than North Atlantic waters at the beginning of the conveyor belt (Sarmiento *et al.* 2004).

1.5 El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) is the largest climate oscillation on Earth to influence ocean currents and surface temperatures. El Niño is the term used to refer to unusually warm surface temperatures in the equatorial region of the Pacific. In contrast La, Niña is the state when there are abnormally cold ocean surface temperatures in the region. During non-El Niño and non-La Niña conditions sea surface temperatures are about 5–8°C warmer in the western than in the eastern tropical Pacific, and the trade winds blow to the west across the region. The sea level is also higher in the western tropical Pacific because of the prevailing winds.

During an El Niño period the sea surface temperatures increase significantly in the eastern tropical Pacific, and the trade winds either slacken or reverse direction, also moving less water from east to west, greatly affecting the physical characteristics of the waters in the regions. However, the effects of El Niño are far more widespread than the Pacific Ocean, and weather patterns and ocean circulation patterns throughout the world are influenced by these events.

The Southern Oscillation part of ENSO refers to the east–west atmospheric circulation pattern characterized by rising air above Indonesia and the western Pacific and sinking air above the eastern Pacific. The strength of this circulation pattern is defined by the Southern Oscillation Index (SOI) which is a measure of the monthly differences in surface air pressure between Tahiti and Darwin. During an El Niño period the surface air pressure is higher in the western tropical Pacific than in the eastern tropical Pacific the SOI has a negative value, and the reverse is true for La Niña periods (Fig. 1.12).

ENSO events generally happen every 4–7 years and can last between 1 and 2 years; however, it seems as though in the 1980s and 1990s El Niño events were more frequent and lasted longer than recorded previously. There was a very protracted El Niño from 1990 to 1995 and exceptionally strong ENSO events in 1992/1993 and 1997/1998.

There is substantial evidence that the SOI is correlated closely to climate anomalies in certain sectors of the Southern Ocean, and that year-to-year variation in sea ice cover in these regions is linked to recent ENSO events. When the SOI is in a positive phase there are generally lower sea-level pressure, cooler surface air, and sea surface temperatures in the Bellingshausen, Amundsen, and Ross Seas, with the potential for greater ice growth. In

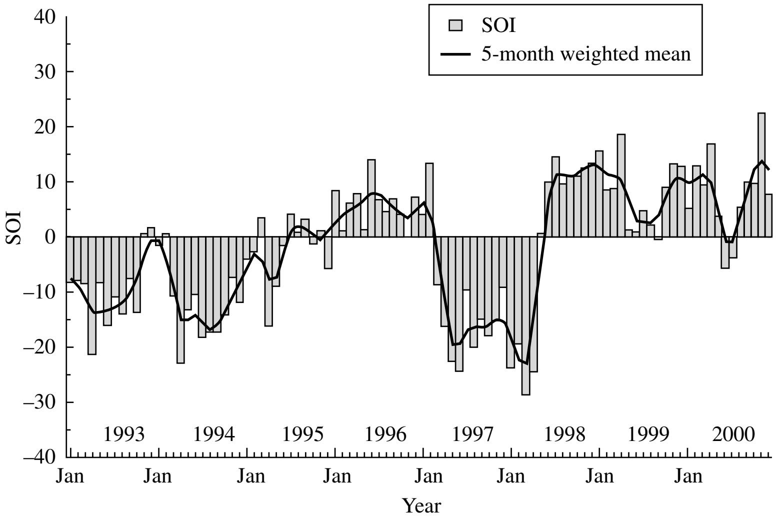

Fig. 1.12 Southern Oscillation Index (SOI) from 1993 to 2000. Redrawn from data presented by the Australian Government's Bureau of Meteorology. Copyright Commonwealth of Australia reproduced by permission.

contrast, during El Niño events (negative SOI) the reverse is true and declines in the ice extent of these regions have been noted. In particular the ENSO years of 1983, 1988, 1992, and 1998 show very good correlations with lower sea ice extents in the Ross Sea in particular. ENSO links to sea ice distribution are not confined to these sectors but are also reported for cyclical sea ice dynamics in other regions of the Southern Ocean.

1.6 Arctic and North Atlantic Oscillations

Over the past few decades it has become clear that many oceanographic trends in the northern hemisphere are closely linked to the North Atlantic Oscillation (NAO). This is one of the most dominant modes of climate variability following El Niño, although there is very little connection between the two. The NAO links the atmospheric pressure distribution between the region of Greenland–Iceland and the subtropical central North Atlantic in the Azores. The NAO index is defined as the difference between the Icelandic low and the Azores high in winter (December to March).

A positive NAO index is characterized by a strong Icelandic low and Azores high pressure with a corresponding strong north–south pressure gradient. When this is the case the pressure differences result in stronger and more frequent storms crossing the Atlantic Ocean towards a more northerly routing. This results in warmer and wetter winters in Europe and the eastern USA in conjunction with cold, dry winters in northern Canada and Greenland (Marshall *et al.* 2001).

During negative phases the pressure gradient is weak with an Icelandic high and Azores low and a south–north pressure gradient. This results in fewer and weaker winter storms crossing in a more-or-less west–east trajectory. They bring moist air into the Mediterranean and cold air to northern Europe and the east coast of the USA, bringing about cold, snowy weather. Greenland has milder winters during these phases.

The *Arctic Oscillation* (AO; sometimes referred to as the *Northern Hemisphere Annual Mode*, or NAM) is thought to be highly linked to the NAO, and in fact some researchers say that the NAO is rather a component of the larger-scale AO, and so often the two terms are interchanged, especially since the variations described by the two are highly correlated. From the 1950s until 1979 a negative phase dominated, after which a more positive phase has predominated. There are years when these general trends are reversed, such as in 1995–1996 when there was a very abrupt reversal of the index (Fig. 1.13).

There has been general warming of surfaces in the Arctic over the past 100 years. However, the increases in the past 20 years has been increasing

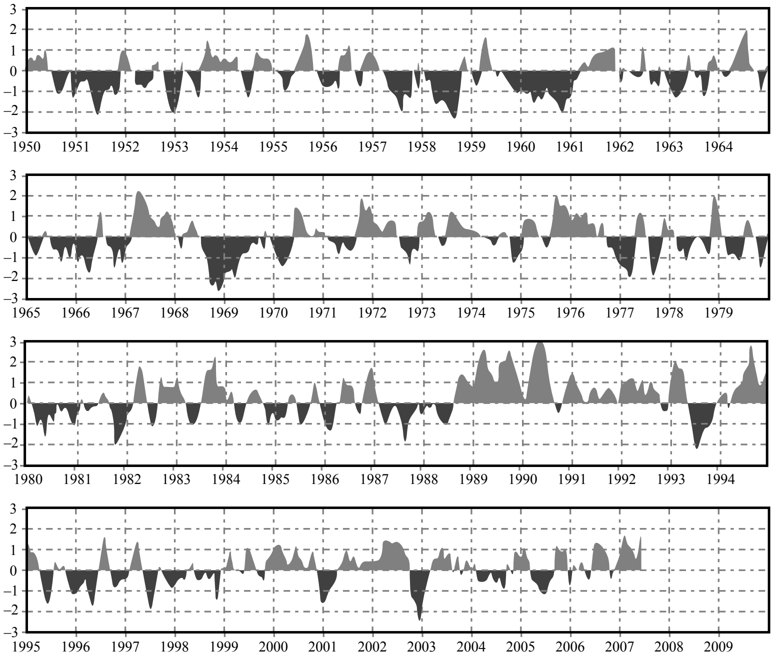

Fig. 1.13 Three-month running mean of the Arctic Oscillation Index from 1950 to present day (May 2007) Image redrawn from data presented by National Weather Service, Climate Prediction Service, National Oceanic and Atmospheric Administration (NOAA).

at a rate eight times higher than the longer 100-year trend which indicates that there has been a rapid acceleration in the warming process linked to global warming processes (Chapter 10). It has also been noted that these rapid warming trends are associated with increasing positive phase in the AO/NAO. Such AO/NAO trends in wind, storm, and warming events will have great influence on the Arctic climate, as is highlighted by interannual variations in sea ice distribution in the Arctic basin (Serreze *et al*. 2007); for example, when the NAO index shifted from positive to negative during the winter of 1995 to 1996 the sea ice export through the Fram Strait is estimated to have been reduced by half.

1.7 Magnetic and electrical phenomena

Investigation of the Earth's magnetic field in the vicinity of the poles was the principal attraction of the Arctic and Antarctic for early scientific expeditions. At the beginning of this century it began to be realized that electrical phenomena in the atmosphere have some relationship with the magnetic field and, in recent years, polar studies have made major contributions to the concept of geospace. Cusps in the magnetosphere, one over each pole, allow the charged particles of the solar wind to penetrate deeply into the polar atmospheres. One manifestation of this is in the aurora (Walton 1987, Pielou 1994). In the present state of our knowledge it seems that this uniquely Polar situation is not of great significance for the life of these regions.

There is a possibility that the fixation of molecular nitrogen produced by the greater electrical activity may support marginal increases in biological productivity. It is also well established experimentally that some organisms react to magnetic fields, and that variations in magnetic fields can affect the time course of plant growth. Birds and mammals may orientate themselves with reference to the Earth's magnetic field so that migrations in the vicinity of the poles may have interesting features. There is a suggestion that magnetic disturbances around the poles may interact with brain activities and interfere with sleep in humans. It may therefore be premature to dismiss the special geophysical characteristics of the polar regions as of no interest to the biologist.