Chapter 25
Recent Climate Change

Causes and Impacts of Climate Change in Antarctica

Michael J. Bentley

Abstract In recent decades, many changes have occurred in the atmosphere and the ocean around Antarctica as well as to the terrestrial environments of the continent itself. The causes of these changes are numerous and varied. All components of the Antarctic environment are linked – the hydrosphere, atmosphere, cryosphere and biosphere all respond to changes in any part of these systems, sometimes resulting in feedback mechanisms that amplify or accelerate changes that are underway. This complexity means that the causes and the consequences of climate change can be difficult to determine but some of the range of physical, biological and chemical impacts of climate change are starting to emerge or are already well established, and future effects can begin to be estimated. There is an extensive and wide-ranging literature on recent Antarctic climate change. In particular there is a comprehensive report by Turner et al. (Antarctic climate change and the environment. SCAR, Cambridge, pp 526, 2009), subject of an overview in Convey et al. (Antarct Sci 21:541–563, 2009).

Keywords Oceanography • Southern annular mode • Sea ice • Larsen B ice shelf • Satellite altimetry

25.1 Antarctic Climate Records

The Antarctic continent has a uniquely short climate record. Apart from a few scattered measurements by early explorers in the nineteenth and early twentieth centuries, the vast majority of Antarctic climate records began in the mid to late 1950s. This coincided with the building of many scientific stations in preparation for the International Geophysical Year (IGY) in 1957/1958. A small number of records predate the IGY, mainly in the Antarctic Peninsula where a precursor to the

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British Antarctic Survey had maintained stations since the 1940s, and on some subantarctic islands such as Orcadas (formerly Laurie Island) where a meteorological record was started by the Scottish National Antarctic Expedition in 1903/1904, and continued thereafter by Argentina.

A second characteristic of Antarctic climate records is that they are mostly concentrated around the coastline: only a small number of records exist from the interior of the continent. Notable exceptions are the US station at the South Pole and the Russian station at Vostok. Determining climate trends in the interior of Antarctica can be challenging and can require use of satellite records in addition to land-based weather stations.

25.2 Climate Changes in Antarctica

25.2.1 Warming of the Antarctic Peninsula

Despite the short period of climate records and their limited distribution, there are some clear trends in the recent climate of Antarctica. The most marked of these is a significant warming along the Antarctic Peninsula. The peninsula is warming faster than anywhere else in the Southern Hemisphere and is amongst the three fastest warming parts of the planet: all of these are high-latitude regions with the other two being north-west North America and the Siberian sector of the Arctic. From 1951 to 2000, the warming trend was 0.56 °C per decade at Vernadsky station (65°S, 64°W, originally called Faraday station) (Fig. 25.1). Most of this warming has been concentrated in the winter months (1.09 °C per decade at Vernadsky) (Turner et al. 2005). Other stations on the Antarctic Peninsula also show this warming. For example, Rothera station, (67°S, 68°W) has warmed by approximately 1 °C per decade, in the period between 1978 and 2000 (Fig. 25.1), and Esperanza (63°S, 56°W) has warmed 0.41 °C per decade in the period between 1961 and 2000, with most of the warming in winter (Turner et al. 2005). For comparison the global average temperature rise in a comparable time interval is 0.13 °C per decade (IPCC 2007).

The warming is most pronounced along the west coast of the Antarctic Peninsula, with less warming on the east side. Total average warming of the peninsula since 1950 has been 2 °C in mean annual temperature, and 6 °C in winter (Stammerjohn et al. 2008).

25.2.2 Climate Trends Beyond the Antarctic Peninsula

For several years, research suggested that although the Antarctic Peninsula was unequivocally warming, the trend of recent change in East Antarctica was one of

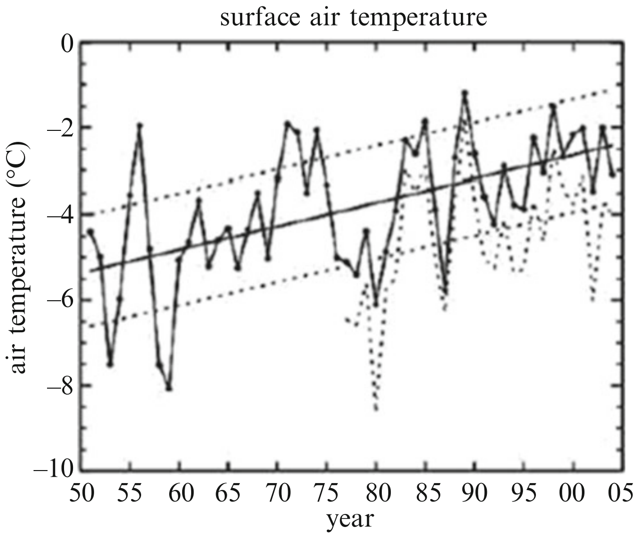

Fig. 25.1 Mean annual temperatures from Faraday/Vernadsky 1951–2004 (*solid line*) and Rothera 1977–2004 (*dashed line*). The *solid trend line* is a linear regression fit with 1 standard deviation (*dashed straight lines*) (Reprinted from Ducklow et al. 2007, with kind permission from the Royal Society)

cooling (Turner et al. 2005). However, the pattern of interior cooling and peripheral warming seen in recent decades is not applicable to earlier intervals in the twentieth century. Satellite-derived climate data and measurements from automatic weather stations provide data over a wide area and show that since 1957 the whole continent has on average warmed up (Steig et al. 2009). This includes persistent warming for the entire period since 1957 of 0.17 °C per decade in West Antarctica (incorporating the peninsula), and a warming for East Antarctica that continued until some time in the 1970s, at which point a small cooling began. But the overall average rate of warming for East Antarctica since 1957 is positive at 0.1 °C per decade. In other words, the East Antarctic cooling detected in earlier studies applies only to the most recent parts of the records (Steig et al. 2009).

25.2.3 Oceanography

Measurements of oceanographic change in the Southern Ocean are sparse. Much information comes from limited ship-based measurements during science cruises, and from automated 'Argo' buoys that transmit water temperature and salinity data

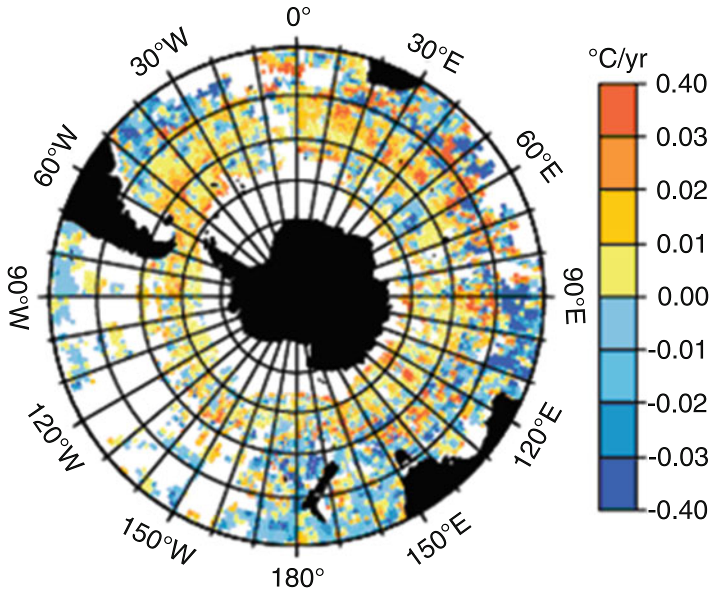

Fig. 25.2 Temperature trends from shipborne measurements and automated float data since the 1950s for the Southern Ocean. Latitude and longitude grid lines are at 10° intervals. Most of the Southern Ocean warming is concentrated in the Antarctic Circumpolar Current (Reprinted from Gille 2002, with kind permission from AAAS)

via satellite (Chap. 7). The period of time for which we have measurements is small compared to other parts of the world's oceans but there are some clear trends in the data. The Southern Ocean shows a warming in recent decades, with many parts also getting fresher (i.e. lower salinity). The Southern Ocean has warmed by an average of 0.17 ± 0.06 °C since 1950 – nearly double the global ocean average amount – and much of this warming has been concentrated in the Antarctic Circumpolar Current, where mid-depth warming has been 0.008° ± 0.002 °C per year (Fig. 25.2) (Gille 2002). This puts it among the fastest warming parts of the global ocean.

Along the western margin of the Antarctic Peninsula there have been particularly marked changes. The surface waters have warmed by more than 1 °C since 1950 (Meredith and King 2005), and the upper 300 m by an average of 0.6 °C (Ducklow et al. 2007).

It is not just ocean temperature that has changed around Antarctica. There has been an increase in meltwater from the ice sheet, an increase in precipitation, and a reduction in sea-ice production locally, which have all led to a freshening of the oceans around parts of Antarctica. For example, repeat oceanographic measurements show that the Ross Sea freshened during the late twentieth century (Jacobs et al. 2002).

25.3 Causes of Climate Change

25.3.1 The Southern Annular Mode

The pattern of peripheral warming and interior cooling has been used to suggest that changes in the Southern Annular Mode (SAM) are behind the climate changes in Antarctica. The SAM is the dominant factor in Southern Hemisphere climate, and is a measure of the relative strength of atmospheric pressure in the interior (or strength of the Antarctic vortex) and the peripheral pressure (or strength of the circumpolar trough) (Chap. 8). The SAM is described as being either positive or negative. In recent decades the SAM has shifted to a more positive mode (Turner et al. 2005), which means that the circumpolar trough around Antarctica has seen a more vigorous circulation (more storms, higher winds, and more mixing of warm air from lower latitudes). The end result has been a significant warming of regions such as the Antarctic Peninsula, which extend into the zone of influence of the circumpolar trough, while at the same time the interior of Antarctica has been cooling in recent decades (Steig et al. 2009).

Recent observations back this up with evidence of a shift of the westerly winds towards the South Pole during the last 40 years. Computer models suggest this is a response to anthropogenic warming (Shindell and Schmidt 2004). More recently, it has been suggested that the Recent Rapid Regional warming (Vaughan et al. 2003) in the northern Antarctic Peninsula is due to increased westerly wind strength, driven by increased greenhouse gas concentrations (Marshall et al. 2006). The shift to a more positive SAM may also be partly related to anthropogenic ozone depletion, which changes the thermal structure of the atmosphere (Chap. 8) (Thompson and Solomon 2002). So it seems that for the Antarctic Peninsula, anthropogenic-induced change in ozone and greenhouse gas concentrations may be driving the climate changes.

25.3.2 The Role of Sea Ice

The marked winter warming of the Antarctic Peninsula is strongly linked to changes in sea ice immediately west (upwind) of the peninsula. During the same time span as the climate warming, winter sea ice to the west of the Antarctic Peninsula has been decreasing in extent by 10 % per decade, and has shortened in seasonal duration. There is a high correlation between the winter air temperatures at Vernadsky Station and the sea-ice concentration to the west of the peninsula: higher temperatures are strongly associated with lower sea-ice concentrations and vice versa (Fig. 25.3). This, along with the most marked warming occurring in winter has led to the suggestion that pronounced warming of the peninsula is at least partly due to reduced sea-ice concentration. Lower sea-ice concentrations can influence climate on the Antarctic Peninsula climate in at least three ways:

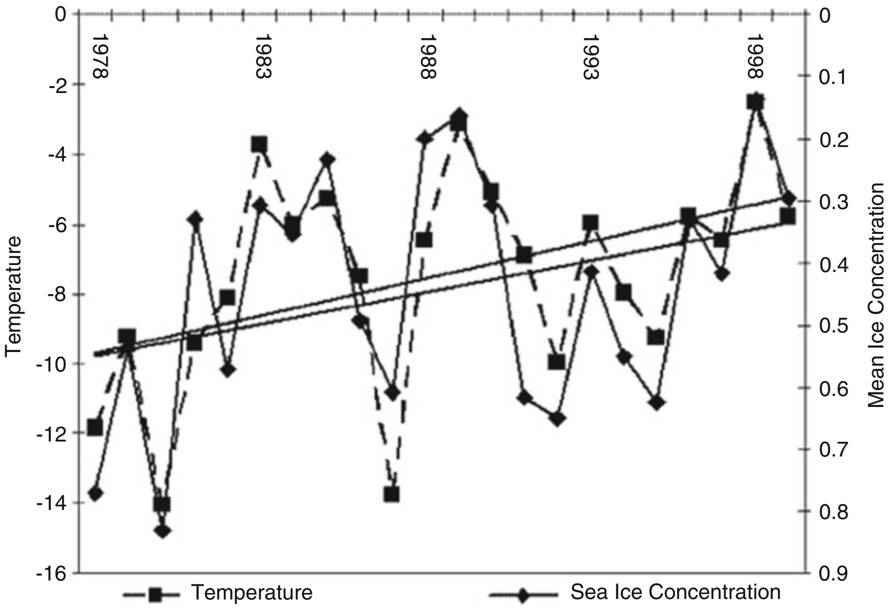

Fig. 25.3 Winter season (June–August) mean sea-ice concentration at 70°W and Faraday/Vernadsky mean winter near-surface temperature. Trend lines produced by linear regression are shown for both time series. Note reversed scale for sea-ice concentration. Warmer temperatures correspond to smaller sea-ice concentrations (Reprinted from Turner et al. 2005, with kind permission from John Wiley & Sons)

- by allowing greater heat exchange from the relatively warm ocean to the atmosphere;
- by reducing the amount of solar radiation reflected back to the atmosphere (the albedo);
- by increasing maritime influence of the nearby land since the open ocean is closer and thus allows warm, moist air masses to penetrate more easily.

All of these factors promote warming and so it is thought that the sea-ice decline west of the peninsula may have contributed to the winter warming.

This relationship is unlikely to exist beyond the Antarctic Peninsula. Satellite data obtained since the late 1970s suggest that elsewhere around Antarctica there is either little change in sea-ice extent, or it may be increasing in extent (Turner et al. 2005; Bintanja et al. 2013). It is important to note that changes in sea-ice conditions result from processes occurring in the atmosphere or ocean and are therefore not the root cause of climate change on the peninsula. However, changes in sea ice have played a key role in amplifying climate change in the western peninsula.

25.3.3 Ocean Warming and Movement of Circumpolar Deep Water

The warming of the ocean west of the Antarctic Peninsula is not fully understood. The warming of surface waters is a response to the warmer atmospheric temperatures (Meredith and King 2005) but the warming at depth may be due to increased movement of Circumpolar Deep Water onto the continental shelf of the peninsula (Chap. 7, Ducklow et al. 2007). The Circumpolar Deep Water is an important intermediate-depth water mass that is relatively warm, and floods onto the continental shelf at only a few sites around Antarctica. Where it does so, it delivers substantial additional heat. This can translate into surface warming when mixing of the top parts of the ocean occurs. The reason for the change in Circumpolar Deep Water is not well-understood but may be related to oceanic circulation changes – in turn influenced by atmospheric circulation patterns (Thoma et al. 2008). This variability can alter the topography of the ocean surface and thus the driving forces for water masses moving in the sub-surface.

25.4 The Physical Impacts of Climate Change

25.4.1 Ice Shelf Retreat and Collapse

One of the most marked effects of climate warming in the Antarctic Peninsula is the abrupt retreat or collapse of ice shelves (Vaughan et al. 2003). In recent decades a number of ice shelves have shrunk to a tiny fraction of their former size, particularly on the east side of the Antarctic Peninsula where the Prince Gustav, Larsen A and Larsen B ice shelves have all collapsed. On the west side, the Wordie and Wilkins ice shelves have mostly disappeared whilst the George VI Ice Shelf has retreated significantly during the same period (Fig. 25.4). Some of these retreats have been spectacularly fast: for example the 3,250 km^2 Larsen B ice shelf collapsed in a matter of just a few weeks in the summer of 2001/2002. Some ice shelves have collapsed previously, during an interglacial period, but have then reformed, whereas for other ice shelves the recent collapse is unprecedented (Hodgson et al. 2006).

Ice shelf collapse in the Antarctic Peninsula is primarily attributed to atmospheric warming (Vaughan et al. 2003). There is a close association between ice shelves that have collapsed and locations where mean annual temperatures are between -9 °C and -5 °C (Morris and Vaughan 2003). Warming above the summer 0 °C isotherm (approximately coincident with the -9 °C mean annual temperature isotherm) leads to melting of the surface of the ice shelf. This melting results in lakes of water that fill crevasses and the pressure of this water can fracture the full depth of the shelf to break it into fragments and force collapse. Melting at the base of ice shelves by relatively warm marine water may also contribute to ice

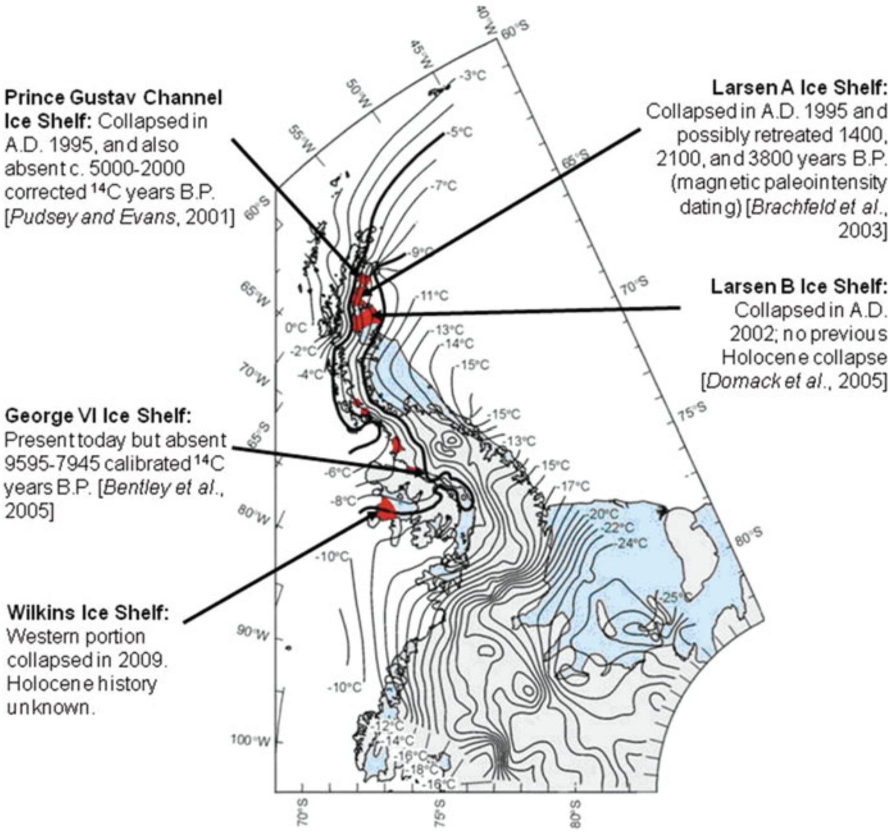

Fig. 25.4 Recent retreat of Antarctic Peninsula ice shelves shown together with the mean annual isotherms. Retreated or collapsed ice shelves (*red*) coincide with the area between the −5 °C and −9 °C isotherms (*bold*). The −9 °C isotherm marks the southern limit of ice shelf stability, south of which there are still extant ice shelves (*blue*). No ice shelves exist north of the −5 °C isotherm. The stability of each ice shelf during the current interglacial (Holocene) is noted (Modified from Hodgson et al. 2006, with kind permission from John Wiley & Sons; original isotherm map courtesy of D. Vaughan, British Antarctic Survey)

shelf collapse, or at the very least make collapse easier by making the ice thinner (Shepherd et al. 2003).

An important effect of the collapse of fringing ice shelves along the Antarctic Peninsula is the acceleration of the glaciers feeding into the former ice shelves (Scambos et al. 2004). Collapse of the ice shelves themselves does not contribute significantly to sea-level rise because they are floating, but they hold back areas of grounded ice inland. As the ice shelves collapse and the buttressing effect is removed, the outlet glaciers thin and accelerate transporting their ice to the ocean and making a direct contribution to sea-level rise. For example, the collapse of the Larsen B ice shelf was followed by acceleration of Crane, Jorum, Hektoria and

Green glaciers that formerly fed into it. The nearby Flask and Leppard glaciers that continued to feed into a remnant portion of the same ice shelf showed little change over the same period (Scambos et al. 2004).

25.4.2 Glacier Retreat and Melting

Eighty-seven per cent of 244 marine-terminating glaciers in the Antarctic Peninsula have retreated since they were first surveyed, indicating marked glacial retreat in the peninsula (Fig. 25.5) (Cook et al. 2005). There is a clear boundary between those glaciers that show mean advance and those that show mean retreat, and this boundary has migrated southwards. The trend is consistent with the atmospheric warming, but this may not be the sole cause of glacier retreat (Cook et al. 2005).

The warming at Vernadsky Station has been accompanied by a 74 % rise in the number of days with temperatures above freezing, implying significant increases in surface melting on the Antarctic Peninsula (Vaughan 2006). However, much of the surface melt re-freezes in the ice sheet and it is not yet known what proportion of this extra melt reaches the ocean as run-off and contributes to sea level rise.

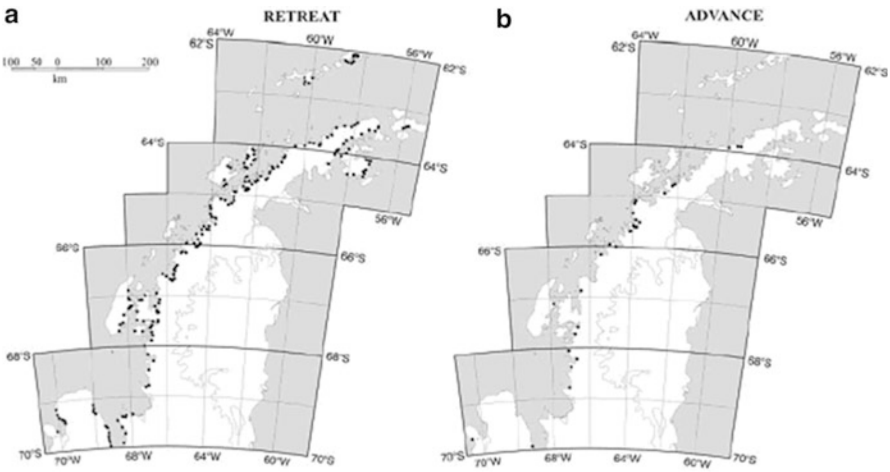

Fig. 25.5 Change in Antarctic Peninsula glacier fronts since the earliest available records. Note that 87 % of the 244 glaciers measured have retreated since first surveyed. Dates of earliest records differ across the region (Reprinted from Cook et al. 2005, with kind permission from AAAS)

25.4.3 Glaciers in the Amundsen Sea Embayment

A major and ongoing change is occurring in the Amundsen Sea embayment. Here a series of major outlet glaciers are thinning, accelerating and retreating. The changes are most pronounced in the Pine Island Glacier but are also occurring in the Thwaites and Smith Glaciers (Fig. 25.6). Thinning of the Pine Island Glacier was first measured in detail in the 1990s but has accelerated markedly since then. In 1995, the lower reaches of the glacier were thinning at an average of 3 m per year

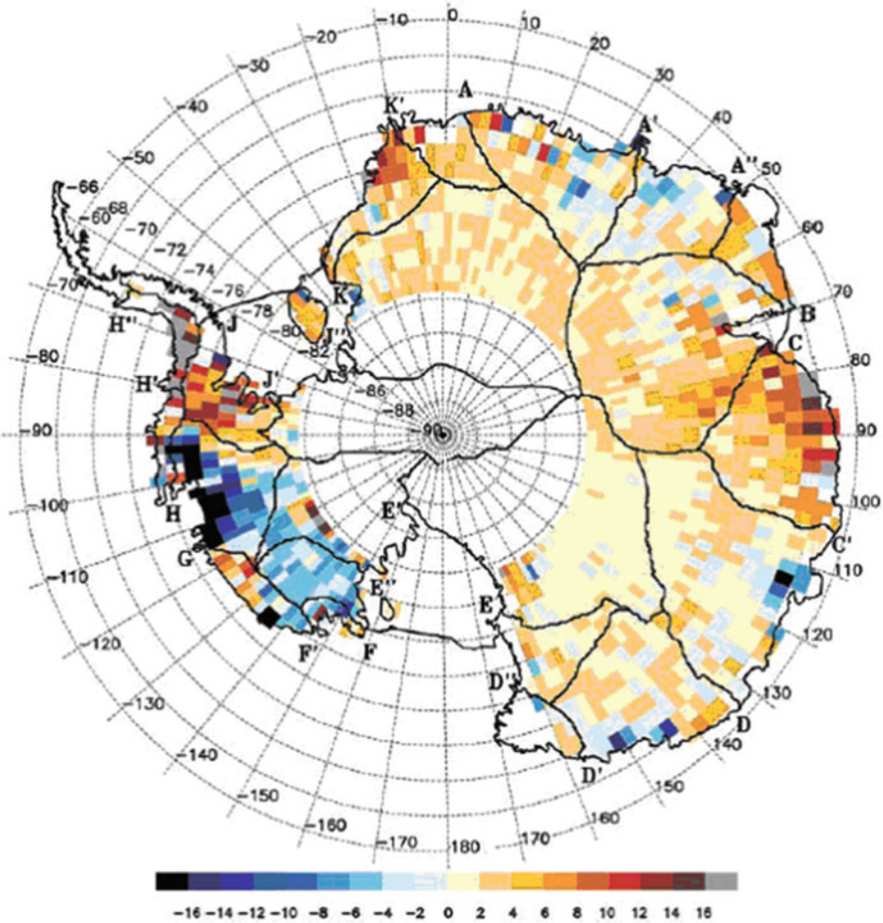

Fig. 25.6 Satellite-altimetry measurements of the elevation change in the Antarctic Ice Sheet 1992–2003. The rapid thinning of glaciers in the Amundsen Sea embayment (−90 to −120 longitude) and the slow rates of thickening of the EAIS are clearly visible. Note that satellite coverage extends to 81.6°S and is considered unreliable in areas of steep topography, hence the lack of data along coastlines and the Antarctic Peninsula (Reprinted from Davis et al. 2005, with kind permission from AAAS)

but by 2006 this had increased to an average of 10 m per year (Wingham et al. 2009). The area affected by thinning has also expanded beyond the main trunk of the glacier and now extends over 100 km upstream and affects both the floating and grounded parts of the glacier. Thinning has also been accompanied by acceleration in velocity, and a retreat of the grounding line (Rignot et al. 2002; Park et al. 2013). The adjoining glaciers have also showed marked thinning and in some cases acceleration and/or retreat. The fastest-moving trunk of the Thwaites Glacier has also widened in recent years.

Such changes cannot be due to changes in precipitation because the thinning is too localised and it would not explain the acceleration and retreat of the glaciers. In addition, the similarity in behaviour of several major outlets over a large area suggests that there is a regional mechanism operating. The most likely mechanism is the intrusion of Circumpolar Deep Water onto the Amundsen Sea shelf (Payne et al. 2004). This warm water causes high rates of melting at the base of the ice, close to the grounding line, and the resultant thinning is transmitted rapidly upstream. This is particularly so in the Pine Island Glacier where the ice is thin and only lightly grounded in its lower reaches. The penetration of Circumpolar Deep Water may be related to changes in the seasonal wind circulation patterns around Antarctica. This is because changes in the winds can modify the transport of water onto the Antarctic continental shelf. The variability of these winds from year to year is consistent with greater delivery of Circumpolar Deep Water during intervals of enhanced thinning and acceleration of the Pine Island Glacier (Thoma et al. 2008).

The overall effect of glaciers in the Amundsen Sea is an ongoing positive (and probably accelerating) contribution to sea-level rise (King et al. 2012). Surveys of topography beneath the ice show that there are deep basins underlying the Pine Island Glacier. As the base of the ice melts and warm water reaches these basins, the ongoing retreat could become unstable and extend deep into the ice sheet. The potential vulnerability of this region was recognised by Hughes (1981) who dubbed the Pine Island Glacier “the weak underbelly of the West Antarctic Ice Sheet”.

25.4.4 Increased Snowfall Over East Antarctica

Satellite measurements of the height of the East and West Antarctic ice sheets above sea level (satellite altimetry) have demonstrated that ice over large areas of the continent is thickening by 1–4 cm per year (Davis et al. 2005) (Fig. 25.6). This growth is particularly clear in the East Antarctic Ice Sheet (EAIS). Growth of the EAIS was predicted by the Intergovernmental Panel on Climate Change (Church et al. 2001) due to the likelihood of increased precipitation in a warming global climate, and it was suggested that the increased snowfall over Antarctica could offset some of the ice loss contributing to sea level. It has now been shown that although this effect exists, the snowfall-driven growth of the EAIS is not enough to offset the loss of ice from other parts of Antarctica such as the Amundsen Sea and the Antarctic Peninsula, and so the continent makes an overall positive contribution to sea-level rise (Velicogna 2009; King et al. 2012; Shepherd et al. 2012).

25.5 Biological Impacts of Climate Change

25.5.1 On Land

On land, the warming climate of the Antarctic Peninsula has been accompanied by a southwards shift in some plant species, and more vigorous growth. There are also some concerns that as the peninsula warms, conditions will become increasingly similar to those on land to the north such as southernmost South America, and that this might mean that successful establishment of species from outside Antarctica becomes more likely (Chap. 27). Over 200 alien species of plants and animals have already been recorded in Antarctica, although most are on the subantarctic islands (Frenot et al. 2005) (Chap. 9). These include a wide range of taxa: microbes, invertebrates, plants and mammals. Not all of these introductions are due to climate change. Some introductions were deliberate and some may have been derived from propogules brought in inadvertently by scientists or tourists. However, it is clear that the potential for alien introductions has been increased by recent climate change. The island of South Georgia has been identified as particularly vulnerable because it is relatively far north, experiencing marked warming and with ongoing glacier retreat that opens up new, previously invader-free, areas, which might be colonised, and is also an increasingly popular tourist destination.

25.5.2 In the Oceans

Warming has direct implications for a range of ocean organisms from penguins to invertebrates. Warming of the atmosphere and waters around the Antarctic Peninsula has been accompanied by local reductions in the ice-dependent Adélie penguin, and rises in the ice-intolerant gentoo and chinstrap penguins (Ducklow et al. 2007). This is thought to be related to the reduction in winter sea ice.

Experiments have shown that even modest warming of the ocean can affect the ability of invertebrates to carry out functions critical to their survival (Peck et al. 2004). For example, the Antarctic scallop (*Adamussium colbecki*) claps its valves together to 'swim' short distances and escape predators. When artificially warmed in aquaria, scallops show a marked loss of this ability; for every 1 °C of warming, about 50 % of the population lose their swimming ability (Fig. 25.7) and by the time waters reach plus 2 °C, none of the population can 'swim'. Similarly, as the surrounding water warms, the bivalve mollusc *Laternula elliptica* quickly loses the ability to rebury itself to escape from predators. These failures in activity are due to loss of aerobic function, and the experiments demonstrate that as little as 2 °C warming of the waters around Antarctica could cause population or species removal (Peck et al. 2004).

Some of the most sensitive species are killed by warming beyond 4 °C. Most Antarctic marine fauna are particularly poorly equipped physiologically to deal with such changes because they tend to be slow growing, long-lived, and relatively slow to reproduce. In addition, the shape of Antarctica and the small latitudinal

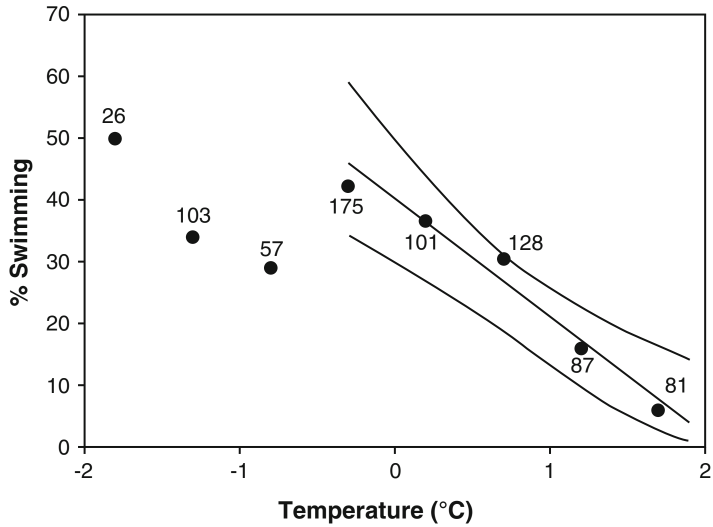

Fig. 25.7 Temperature-related loss of critical functions in marine invertebrates. The plot shows the percentage of a population of *Adamussium colbecki* able to swim away from a freshwater stimulus, at a range of experimental temperatures. Numbers beside data points refer to the size of the experimental population. Above −0.3 °C there is a trend of decreased swimming ability shown by the central trend line (Reprinted from Peck et al. 2004, with kind permission from John Wiley & Sons)

range of the coastline means there is little opportunity to migrate away from such changes. Together these factors imply that Antarctic marine invertebrates may be one of the major animal groups threatened by climate change.

As with ecosystems on land, there are concerns that as the ocean warms the establishment of alien species from further north becomes more likely. However, much less is known about introductions to the marine environment, partly because it is less well surveyed in general than the terrestrial environment. So far only one marine invader has been confirmed: a species of spider crab from the North Atlantic that may have been introduced from ship's ballast water (Frenot et al. 2005).

25.6 Biogeochemical Cycles

The Southern Ocean is an important part of the global carbon cycle, one of several biogeochemical cycles on the planet. The ocean contains dissolved carbon dioxide (CO_2) and there is exchange of this carbon with the atmosphere (Chap. 8). The Southern Ocean can potentially act as a sink (or 'reservoir') for CO_2. Such sinks are crucial because they limit the increase in atmospheric CO_2 concentrations to only half the emitted amounts: in other words, sinks such as the Southern Ocean absorb half of what is emitted by human activities. The precise magnitude of the Southern Ocean sink is disputed but recent work suggests that the amount absorbed has gone down between 1981 and 2004 by 0.08 Pg carbon per year (1 Pg = 1 billion tonnes) (Le Quéré et al. 2007). The change is probably because of the observed increase in surface winds over the Southern Ocean, which can reduce CO_2 uptake by the ocean. The reduction happens because the stronger winds 'stir up' the ocean and cause it to release much of its dissolved CO_2. This trend is predicted to increase and atmospheric concentrations of CO_2 may reach higher concentrations than if the uptake had continued at its earlier rate.

More recent work has suggested that the retreat of ice shelves and glaciers along the Antarctic Peninsula has opened up new areas of open water and that there may be increased surface water plankton productivity in the region (Peck et al. 2009). If this is the case then carbon will be extracted from the atmosphere by plankton and then deposited on the seabed as they die, so these areas will act as new sinks for carbon. Peck et al. (2009) have shown that the new biomass created is several times greater than that lost by deforestation of a comparable area in the tropics, and that a significant fraction of the biomass will be deposited to the seabed. This recently discovered effect is important as it could potentially act as a negative feedback on greenhouse-gas induced climate change.

25.7 Summary

Recent climate change in Antarctica has occurred in both the atmosphere and oceans. Atmospheric warming has been most pronounced in the Antarctic Peninsula – one of the fastest warming regions on the planet – but is not restricted to this area. Similarly ocean warming has been marked in the waters west of the Antarctic Peninsula but most of the Southern Ocean is warming at a rate faster than the global average. The warming is at least partly due to anthropogenic effects of increased greenhouse gases and ozone depletion, but the effects in the Antarctic Peninsula are amplified by a significant loss of winter sea ice.

These changes have had a range of impacts, both physical and biological. These include the abrupt loss of ice shelves along the Antarctic Peninsula, accelerated movement of feeder glaciers and retreat of marine-terminating glaciers. In the Amundsen Sea embayment major outlet glaciers are thinning, accelerating and retreating. There is concern that these changes may result in an unstable retreat of a significant part of the West Antarctic Ice Sheet. The East Antarctic Ice Sheet is experiencing slow growth from increased precipitation associated with a warmer atmosphere but this is not sufficient to offset the ice mass loss in the Antarctic Peninsula and Amundsen Sea embayment, and overall Antarctica is making a net positive contribution to sea-level rise.

Biological impacts of climate change are diverse and include changes in species composition and range, and the increasing likelihood of alien species being introduced. In marine ecosystems, many invertebrates lose critical functions after even quite modest warming. Biogeochemical cycles are affected by changes in the ability of the Southern Ocean and Antarctic coastal waters to 'fix' carbon and act as a sink for some of the anthropogenic input to the atmosphere.

This chapter has highlighted recent advances in Antarctic climate research, and shown that major progress has been made in monitoring and understanding the Antarctic climate, both in the atmosphere and the oceans. However, robust predictions of what Antarctica and its climate will look like in the future are still hampered by a lack of understanding of some of the processes involved, and the complex connections between them.

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