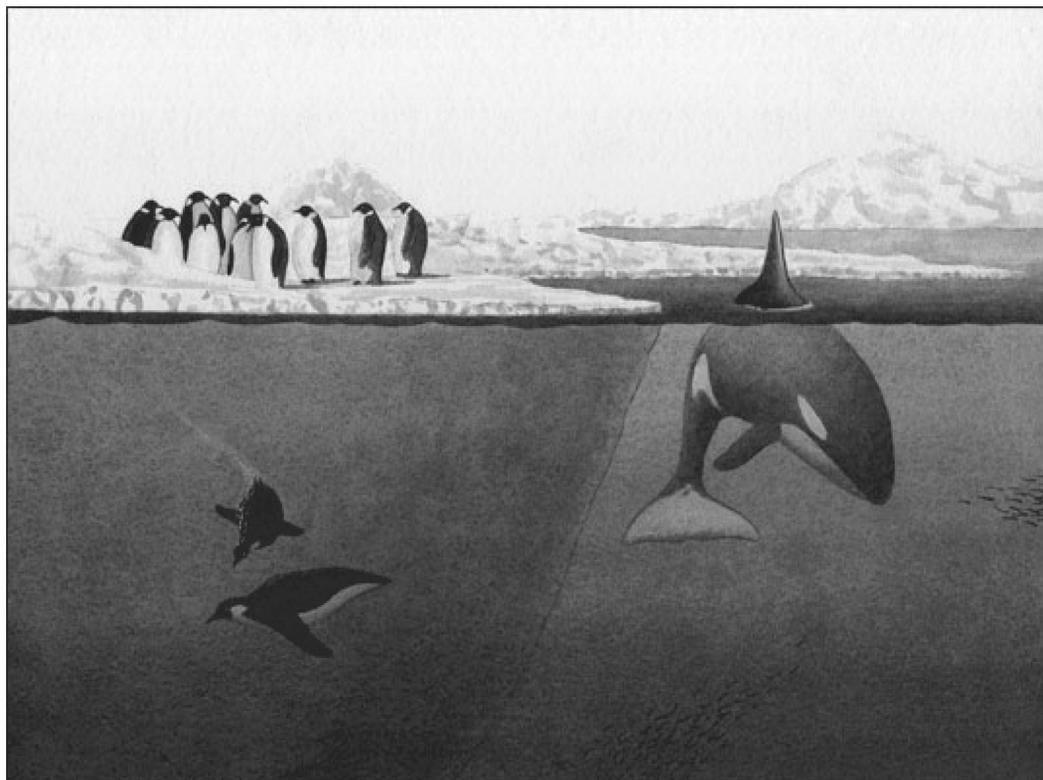


## 21 • Polar and ice-edge marine systems

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### INTRODUCTION

Cold, seasonal and dominated by ice, the two polar regions are similar in many ways. Oceanographically, however, they are very different. The Arctic is a deep basin surrounded almost completely by extensive shallow continental shelves and continental land masses. Large river systems (Chapter 2) discharge significant volumes of fresh water and sediment into the Arctic basin, some of them carrying substantial pollution, and exchange with the

Pacific and Atlantic Oceans is highly constrained. In direct contrast, the Antarctic is a single isolated land mass surrounded on all sides by a deep ocean contiguous with the three great ocean basins (Fig. 21.1).

Climate change has been identified as the key environmental trend in both polar regions, with the most likely effect in the marine environment being mediated through changes in sea-ice dynamics (Clarke & Harris 2003) (Table 21.1). The polar regions play a critical role in the

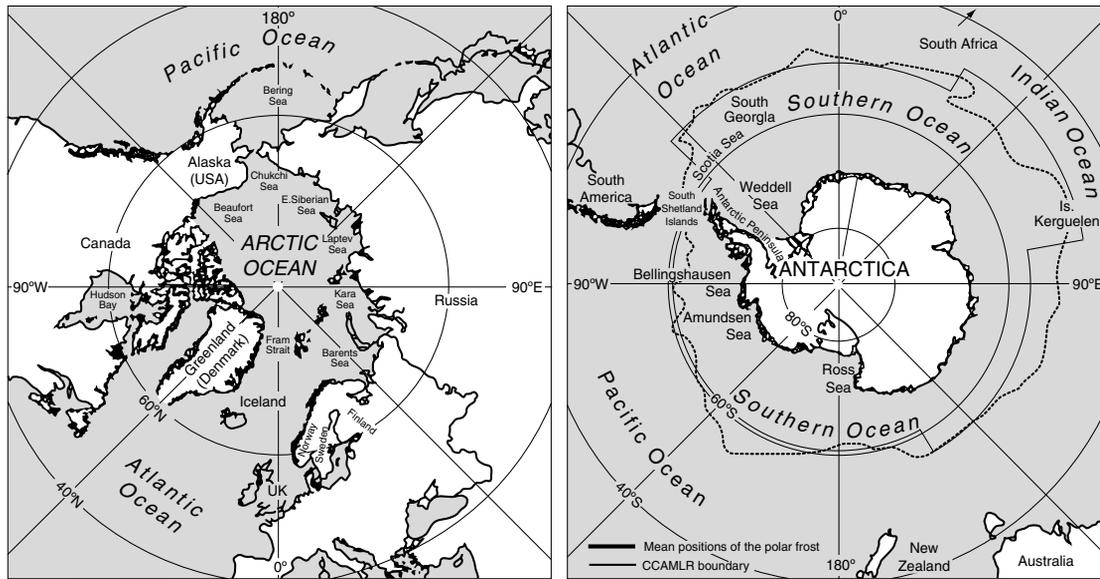


Fig. 21.1. The Arctic and Antarctic, showing the differences in topography and connections to lower latitude oceans. In the Antarctic, the dotted line shows the mean position of the

Antarctic Polar Front. CCAMLR, Commission for the Conservation of Antarctic Marine Living Resources.

regulation of global climate, and it is expected that future climatic shifts will be particularly pronounced at high latitudes (IPCC [Intergovernmental Panel on Climate Change] 2001a). The precise patterns of change and the feedbacks that influence these are, however, poorly understood and our ability to predict the future is greatly limited by this uncertainty.

### Major Arctic trends

Current expectations are that the Arctic region will be the first to experience substantial climate change, with a possible rise in average surface air temperature of 4–5 °C by the middle of this century (Stouffer *et al.* 1989; Manabe *et al.* 1991; IPCC 2001a). Increases in spring and summer air temperatures have already been detected (Martin *et al.* 1997), and both thinning and a decrease in spatial extent have been described for Arctic sea ice (Maslanik *et al.* 1996; Parkinson *et al.* 1999; Wadhams & Davis 2000; Rothrock *et al.* 2003). The IPCC (2001a) concluded that average Arctic sea-ice extents had declined by 15% in summer and 8% in spring, and there is some evidence that the rate of reduction may have been accelerating in recent years (Johannessen *et al.* 1995).

Reductions in sea-ice cover will have important oceanographic consequences, driven by changes in air–sea exchanges, irradiance and water-column stability. There are also probable impacts on Arctic marine biota at all levels in the food web (Tynan & DeMaster 1997). In addition, there has been a direct impact on the Arctic marine system through fishing and hunting. Many Arctic marine mammals have been overexploited in the past (Pagnan 2000) with many species still globally endangered. New developments in fishery technology have also increased the scale of fish catches in the Arctic, and overharvesting has led to the collapse of stocks of several species (Pagnan 2000).

Human activities have also had a major influence on the Arctic through the dissemination of pollution from both local and global sources (AMAP [Arctic Monitoring and Assessment Programme] 1998). These contaminants include persistent organic pollutants, heavy metals, acid rain, sulphur deposition, hydrocarbons from oil and gas extraction, and radioactivity. Industrial chlorinated hydrocarbons have also led to the depletion of stratospheric ozone over the Arctic (Pyle 2000). This pattern of pollution reflects both the long-distance dispersal from industry at lower latitudes and the topography of the Arctic as a basin almost completely surrounded by continental land masses.

Table 21.1. Summary of major environmental trends and principal threats to polar marine ecosystems

Category	Threats and trends
<i>Arctic</i>	
Environmental trends	(1) Some evidence for significant change in sea-ice extent and thickness in Arctic Ocean, though spatial patterns of change non-uniform (2) Moderate ozone depletion (3) Fishing has severely depleted stocks of fish and some marine mammals
Threats (long-term)	(1) Climate change, with consequent impacts on sea ice, hydrological cycle and UV-B flux
Threats (short-term)	(1) Fishing impact (2) Mineral extraction (especially pollution impacts)
<i>Antarctic</i>	
Environmental trends	(1) Significant atmosphere warming in Antarctic peninsula, but not over continent (2) Significant depletion of springtime ozone levels since c.1970, with consequent increase in UV-B flux. Believed to have peaked, with improvement expected over next 25 years (3) Significant decrease in extent of winter sea ice in Bellingshausen/Amundsen seas, but not in other sectors, since advent of satellite observations. Longer-term trends contentious (4) Southern Ocean fishery has severely depleted stocks of some fish, and some marine mammals. Recovery of fish and whale stocks slow; southern fur seal stock recovery rapid. Fishing outside Southern Ocean has by-catch impact on some seabirds that breed south of the Antarctic Polar Front, especially albatrosses and larger petrels
Threats (long-term)	(1) Climate change in Antarctic peninsula area, with consequent impacts on sea ice
Threats (short-term)	(1) Illegal, unreported and unregulated (IUU) fishing activity, both in terms of impact on exploited stocks and on seabird by-catch

Source: From Clarke and Harris (2003).

### Major Antarctic trends

Environmental trends in the Antarctic are similar in many ways to the Arctic, with climate change, stratospheric ozone depletion and fishing pressure being the most important. Pollution is currently much less of a threat to the Southern Ocean than in the Arctic (Clarke & Harris 2003). It is, however, difficult to detect any clear environmental trends for the Antarctic marine ecosystem as a whole, although there are localized trends in some areas. The Antarctic Peninsula is warming rapidly, but the Antarctic continent itself shows no spatially consistent trend (King 1994). The reason for this difference is not clear, though the climate of the Antarctic Peninsula area is highly sensitive to the complex feedbacks between atmosphere, oceans and sea ice, and is strongly influenced by climatic variations in the subtropical and tropical Pacific Ocean (King & Harangozo 1998; Yuan & Martinson 2000, 2001).

In recent years, a reduction in sea ice in some areas (Jacobs & Comiso 1993) has been balanced by an increase in others, and there is currently no evidence for a decline in overall sea-ice extent around Antarctica (Zwally *et al.* 2002). The Amundsen and Bellingshausen Seas have shown a significant decrease in sea ice, however, and this may be related to the regional climate warming of the Antarctic Peninsula. In the western Antarctic Peninsula region, sea-ice extent has decreased with consequent impact on all trophic levels of the marine ecosystem (Smith *et al.* 2003a, b). This may offer a valuable analogue for future changes elsewhere in polar regions.

Like the Arctic, the Southern Ocean living resources have a long history of human exploitation. Following the exploratory voyage of Captain James Cook in the eighteenth century, a fishery for southern fur seal (*Arctocephalus gazella*) developed rapidly. By 1822, a period of only 35 years, the industry collapsed (Bonner 1982), and exploitation shifted to the great whales. By the late 1960s, whale stocks

had been severely depleted and attention switched to finfish, the exploitation of which continues today, together with a fishery for Antarctic krill (*Euphausia superba*).

In this chapter, the predominant environmental trends and threats identified by Clarke and Harris (2003) are used as a basis for predicting likely states of the two polar marine environments in 2025. Climate, ozone, sea ice and fishing are separately addressed, and the chapter concludes with a discussion of how human influences might be mitigated by regulatory actions.

## CLIMATE

The future of both the Arctic and Antarctic marine ecosystems is linked very closely with climate change. During the past decade, the polar regions have exhibited many of the first unmistakable signs of climate warming, and the ecological manifestations of this warming are magnified by its dramatic impact on sea-ice cover. Observationally, climate warming throughout much of the Arctic, and in Antarctic locations particularly relevant for marine ecology, is well established (e.g. Stammerjohn & Smith 1996; Rigor *et al.* 2000). Satellite passive microwave observations have documented the significant retreat of Arctic sea-ice cover, along with a slight but statistically significant increase in Antarctic sea-ice cover when averaged over the entire Southern Ocean (Cavalieri *et al.* 1997; Johannessen *et al.* 1999; Zwally *et al.* 2002). These trends in sea-ice cover in both hemispheres are consistent with predictions from global climate model (GCM) simulations (Cavalieri *et al.* 1997; discussed below). The sea-ice retreat in the western Antarctic Peninsula region has not yet been reproduced in GCM simulations, although a plausible mechanism was proposed by Thompson and Solomon (2002). The mechanisms behind high-latitude climate warming are dynamically very complex, but are very likely to have an anthropogenic component.

### Feedbacks in the polar climate system

For many years, high-latitude climate warming has been expected as a result of classical climate-feedback mechanisms involving surface albedo (the ratio of reflected to incident electromagnetic radiation), solar and terrestrial radiation, and cloud cover (Crane & Barry 1984; Somerville & Remer 1984; Ledley 1993; Curry & Webster 1999). In the ice-albedo feedback, which should be significant at temperatures close to the triple-point of water, a warming

induces a localized melting of snow or ice, which thereby reduces the surface albedo. This reduced albedo leads to enhanced absorption of short-wave radiation by the surface, which thus accelerates the melting rate and further decreases the albedo. The result is a reduction in short-wave radiation backscattered to space by the Earth-atmosphere system, a concomitant increase in shortwave absorption by the surface and a decrease in snow/ice cover, which together constitute a strong positive feedback to climate warming. A warmer climate may also allow the atmosphere to hold more water vapour, and this water vapour will partially close infrared windows (the wavelength ranges over which the atmosphere is largely transparent to radiation) such that atmospheric long-wave emission warms the surface to a greater extent. This water-vapour feedback is another potentially important positive feedback at high latitudes (Curry *et al.* 1995). There is also a general cloud-radiation feedback (Curry & Webster 1999), through which changes in atmospheric precipitable water force changes in cloud amount, vertical distribution, optical depth, thermodynamic phase, effective droplet radius and ice particle size and temperature. The present consensus is that the net effect of these feedback mechanisms should be positive at high latitudes, although analysis of trends in satellite temperature data has challenged this conclusion (Wang & Key 2003). In contrast to these positive feedbacks, a negative feedback can arise if there is increasing precipitation on sea ice resulting from a warming atmosphere containing more moisture (Ledley 1993). In this scenario, the snow cover build-up increases the surface albedo, thus decreasing the absorbed short-wave radiation, and also decreases the turbulent energy flux from the ocean to the atmosphere.

### The Arctic Oscillation

Recent research in atmospheric dynamics has introduced a new perspective on high-latitude climate change. Thompson and Wallace (1998) identified the Arctic Oscillation (AO), a persistent mode of variability in atmospheric circulation, as a major regulator of Arctic surface temperature. In its simplest conception, the AO can be thought of as a see-saw in sea-level pressure, alternately rising over the central Arctic Ocean and then in a sub-Arctic belt ranging from southern Alaska to Europe. The AO and the North Atlantic Oscillation (NAO) index which has been known for several decades are often considered part of the same dynamic phenomenon, the

Northern Annular Mode (NAM), although this view remains somewhat controversial. Physically, the NAM is manifest as an oscillation in the strength of counter-clockwise zonal atmospheric flow at temperate and high latitudes. Two important aspects of annular modes are relevant to climate change. Firstly, they do not necessarily vary in a periodic way; they can vary both monthly and annually. Secondly, annular modes are easily excited by external physical forcing such as atmospheric warming.

The interaction between the AO and climate is described by the AO index, defined as the leading principal component of the wintertime (November–April) monthly mean sea-level pressure anomaly field poleward of 20° N. In the positive phase of this oscillation (high AO index), stronger westerlies isolate colder air to the north, allowing Arctic temperatures at many locations to become warmer. In the negative phase (low AO index), there are relatively weak westerly winds, and colder air is allowed to spill out further south at most longitudes. During the past two decades, there has been a shift toward a positive phase in the NAM, and this may be the direct cause of much of the observed Arctic warming (Thompson & Wallace 2001).

In addition to this direct effect on Arctic surface air temperatures, the AO has been dynamically linked to Arctic sea-ice concentrations (Rigor *et al.* 2002). During low AO index conditions there is a substantial clockwise circulation in the Beaufort Gyre, which confines much sea ice into the colder central Arctic where it tends to thicken. During high AO index conditions this circulation weakens, ice residence time in the central Arctic is reduced, and there is a more rapid passage of ice through the Fram Strait into the North Atlantic. The AO thus has both thermodynamic and direct dynamic impacts on Arctic sea-ice cover.

Although the NAM mechanism would appear to lessen the role of direct greenhouse and similar forcings in high-latitude warming, these anthropogenic factors may still have a prominent indirect role. Current GCM simulations are beginning to reproduce the NAM (Moritz *et al.* 2002), and some models suggest that a strengthening of the AO may result from anthropogenic greenhouse forcing (Shindell *et al.* 1999).

### The Southern Annular Mode and Antarctic ozone

The springtime decrease in stratospheric ozone over Antarctica (Fig. 21.2), popularly known as the ozone hole, is one of the first large-scale atmospheric changes to have a

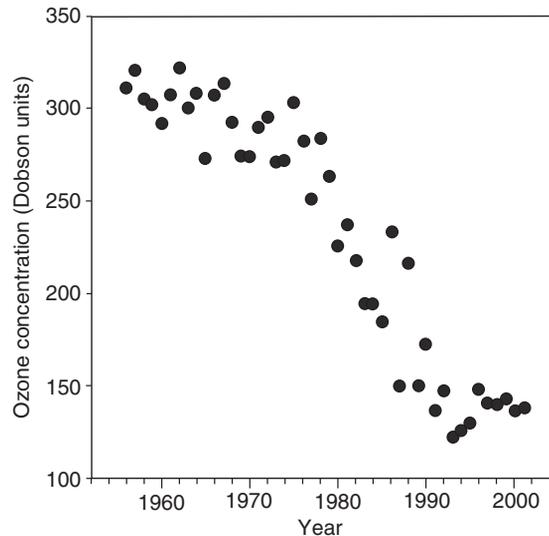


Fig. 21.2. Monthly mean total ozone in October, the month of minimum ozone levels above the British Antarctic Survey research station at Halley (British Antarctic Survey data).

proven human origin. Initial concern about the onset of the ozone hole during the 1980s involved dramatically enhanced solar ultraviolet (UV) radiation (Lubin *et al.* 1989) and possible damage to the Antarctic marine food web. Inhibition of photosynthesis in Southern Ocean phytoplankton, directly attributable to enhanced UV radiation in the upper water column, has been reported (Smith *et al.* 1992; Holm-Hansen *et al.* 1993). However, satellite remote sensing of ocean colour suggests that the Antarctic ozone hole has probably not caused irreparable damage to the Antarctic marine ecosystem through enhanced UV radiation (Arrigo *et al.* 1998), although it is difficult to distinguish long-term change against the background of intense year-to-year variability. Nevertheless, ozone-related increases in UV-B radiation are well documented and may interact with other environmental factors to influence productivity in marine systems (Hader *et al.* 2003). They may also affect biogeochemical cycles in ways that influence overall system productivity and dynamics (Zepp *et al.* 2003).

In terms of climate, one important aspect of the Antarctic ozone hole lies in its interaction with the Southern Annular Mode (SAM), the Antarctic equivalent of the NAM (Thompson & Wallace 2000). Recent observations indicate a trend towards stronger westerly circumpolar flow, related to a high SAM index, over the last few decades (Thompson *et al.* 2000b). Thompson and Solomon

(2002) suggested that this trend was dominated by the development of the Antarctic ozone hole, and associated stratospheric radiative cooling related to the low ozone abundances. This is because observed changes in southern hemisphere stratospheric circulation are strongly related to total column ozone. Furthermore, analysis of geopotential heights indicates similar and concomitant trends towards a high-index polarity of the SAM occurring in the tropospheric circulation, but with some timing differences (Thompson & Solomon 2002). This implies a coupling between the SAM in the troposphere and the circulation in the lower stratosphere. Theoretical predictions suggest that the stratosphere–troposphere coupling should be the strongest when the polar vortex is either building or decaying, and observations indicate that this is indeed the case and therefore the impacts of the springtime ozone losses on the lower stratosphere extend to the circulation of the troposphere. A significant portion of the trends in the surface temperature anomalies over the Antarctic continent (cooling over eastern Antarctica and the Antarctic plateau with a concurrent warming over the Antarctic Peninsula) could be explained by the SAM and related strengthening of the tropospheric westerlies in high SAM index conditions (Thompson & Solomon 2002).

### High-latitude climate changes

The Arctic Ocean and the western Antarctic Peninsula are strongly influenced by changes in atmospheric dynamics that most likely have substantial anthropogenic origins, from both greenhouse warming in the troposphere and ozone depletion in the stratosphere. Anthropogenic ozone depletion is expected to persist for another three or four decades before significant recovery occurs under the Montreal Protocol. The most comprehensive assessments of climate change suggest a continued warming trend (IPCC 2001*a*). It is therefore reasonable to expect that these climate-related ecological changes, linked to high AO and SAM index conditions, will continue to the 2025 time horizon.

### SEA ICE

The annual growth and decay of sea ice is one of the most prominent physical processes on Earth. Historically, Arctic sea-ice extent has varied between a summer minimum of about 7–9 million km<sup>2</sup> and a winter maximum of 15–16 million km<sup>2</sup> (Parkinson 2000). In the Antarctic, sea-ice extent has oscillated between a summer (February)

minimum extent of approximately 4 million km<sup>2</sup> and a winter (August) maximum of 20 million km<sup>2</sup> (Zwally *et al.* 2002). Some Arctic sea ice may persist for tens of years and form ridges more than 10 m thick (Maykut 1985), whereas most Antarctic sea ice lasts only one year and has a mean thickness of less than 3 m (Horner *et al.* 1992; Thomas & Dieckmann 2003).

The annual cycle of freezing and melting of sea ice has a profound oceanographic impact, leading alternately to the formation of cold dense high-salinity water during ice formation and to surface-stabilizing low-salinity water when the ice melts. This process in turn comprises a significant driver of global thermohaline circulation. The seasonal presence or absence of ice also has an important climate effect, influencing solar heat reflection or absorption (albedo), and mediating ocean–atmosphere interactions. In addition to influencing globally significant physical processes, sea ice provides habitats of major ecological importance. Numerous organisms live in or on, or are associated with, sea ice for some or all of their life cycle, and sea ice influences biological processes at all trophic levels. Sea ice is both an indicator of change and, via strong feedback systems, a mechanism affecting global climate. Further, sea ice is a major element of the polar environment and associated ecosystems. If the impact of climate variability is to be predicted, it is therefore essential that the variability and long-term trends in sea ice be understood.

Observations on ice thickness and extent come from historical sources such as whaling records or travel diaries, polar stations, ships, submarines, aircraft and satellites. Polar stations, while limited spatially, provide the longest time-series records. Conversely, passive-microwave satellite instruments can measure the global sea-ice cover every few days with a resolution of the order of 25–50 km, thus providing good spatial and extremely good temporal resolution. However, satellite data are available only for the past two decades and currently can provide no quantitative information on ice thickness (and hence volume), although the next generation of satellites will do so. All observations show very large seasonal variations in the thickness and extent of the sea-ice field. In spite of this variability, there are numerous reports of statistically significant changes in sea-ice extent and duration around both poles in recent decades.

### Arctic sea ice

In the Arctic, field observations suggest that sea-ice reduction began in the 1960s (Fig. 21.3), and analyses of

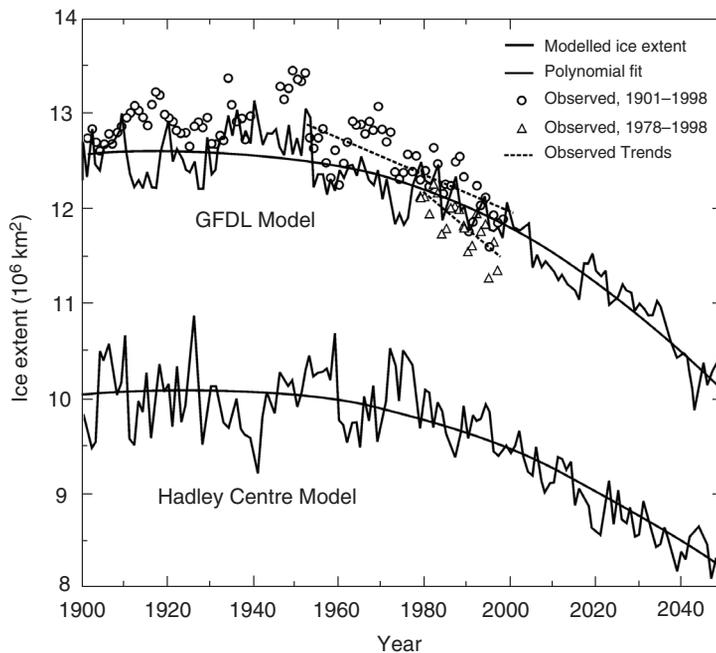


Fig. 21.3. Observed and modelled changes in sea-ice extent in the Arctic. Output is shown from two models, namely the Geophysical Fluid Dynamics Laboratory (GFDL) model and the Hadley Centre HadCM3 model. Although these models

assume different ice extents at the start of the twentieth century, both show a decline in Arctic sea ice from the 1960s. The observed data (IPCC 2001a) also show a decrease in sea-ice extent from the 1960s.

satellite data suggest the rate of reduction has proceeded at roughly 3% per decade over the period 1979–96 (Serreze *et al.* 1995, 2000; Cavalieri *et al.* 1997; Johannessen *et al.* 1999; Parkinson *et al.* 1999; Deser *et al.* 2000). Decreases in Arctic sea-ice extent have occurred in all seasons although there is evidence for a stronger reduction in summer (4–6% per decade) compared with autumn and winter (0.6% per decade) (Chapman & Walsh 1993; Maslanik *et al.* 1996; Cavalieri *et al.* 1997; Parkinson *et al.* 1999; Vinnikov *et al.* 1999; Deser *et al.* 2000). Satellite observations permit the evaluation of trends by regions, and all regions show a statistically significant decrease in sea-ice cover over the past two decades (Parkinson *et al.* 1999).

Forty-year (1958–97) records of reanalysis products and corresponding sea-ice concentration data, combining conventional surface estimates with microwave satellite data, indicate that the recent and historically unprecedented trends in the wintertime NAO and AO circulation patterns over the past three decades have been imprinted upon the distribution of Arctic sea ice (Chapman & Walsh 1993; Deser *et al.* 2000). This and other work (Zhang *et al.*

2000; Hall & Visbek 2002) is consistent with the hypothesis that atmospheric circulation anomalies force the sea-ice variations. Over this 40-year record, Deser *et al.* (2000) showed a nearly monotonic decline (–4% per decade) in summer sea-ice extent for the Arctic as a whole.

The data for longer timescales are sparse, and there is a diversity of conclusions that Polyakov *et al.* (2003a) suggested was caused by problems in sampling spatially and temporally very variable ice thickness and extent. Making use of newly available historical Russian records from five polar stations spanning the Kara, Laptev, East Siberian and Chukchi Seas, Polyakov *et al.* (2003a, b) used a century-long time series to evaluate trends and long-term variability of August ice extent in Arctic marginal seas. Their analysis concentrated on fluctuations with a period of 50–80 years, and they argued that these low-frequency oscillations (LFOs) have played an important role in Arctic sea-ice variability. Time-series and wavelet analyses of these data from the Siberian marginal ice zone indicate two periods of maximum ice extent associated with positive LFO phases (and warming in the 1930s–1940s and

late 1980s–1990s), and two periods of maximum ice extent associated with negative LFO phases (and cooling prior to the 1920s and in the 1960s–1970s). Analyses of these long-term, but regionally specific, data suggest that long-term trends are small and generally statistically insignificant (Polyakov *et al.* 2003*a, b*). This work shows the value of long-term records that permit analysis of low-frequency variability. It is also consistent with the more recent satellite-based analyses that show very large inter-annual variability among the various Arctic sea-ice regions, and emphasizes why a general conclusion for the Arctic as a whole cannot be generated from limited spatial observations.

Observations of sea-ice thickness are more restricted in both space and time. Holloway and Sou (2002) provided a recent review and analyses of ice-thickness observations. Ice draft data from submarine-based sonar profiling have led to a wide range (0–43%) of estimated trends in reduction of ice volume (Bourke & Garrett 1987; Bourke & McLaren 1992; McLaren *et al.* 1994; Shy & Walsh 1996; Rothrock *et al.* 1999; Wadhams & Davis 2000; Tucker *et al.* 2001; Winsor 2001). Holloway and Sou (2002) argued that these results are not necessarily contradictory, given the different time periods and locations of data. Indeed, all investigators have found large interannual and spatial variability. By making use of other data (atmosphere, rivers and ocean) in a dynamic ocean–ice–snow model, these authors attempted to constrain the inferences from the submarine-based data. Volume loss from 1987 to 1997 lies within the range of 16–25% and suggests that reports of more rapid loss are inconsistent with their more comprehensive data and model constraints (Holloway & Sou 2002). The best current estimates thus indicate a significant loss of Arctic sea-ice volume over recent decades.

An alternative perspective is provided by the use of models, making use of ice, ocean and atmospheric parameters, which permit longer time-series data to be used to examine sea-ice trends and explore the driving mechanisms associated with these trends. A thickness distribution sea-ice model coupled to an ocean model suggests that during the past two decades, the ice system has reacted to climate variability primarily through changes in ice advection, resulting in a change in distribution of ice mass rather than in thermal forcing (Zhang *et al.* 2000). Changes in Arctic ice cover may be responses to changes in atmospheric circulation and appear to be an integral part of the NAO and AO (Zhang *et al.* 2000). Linking ice dynamics to atmospheric

variability will be an important factor in distinguishing periodic behaviour from long-term trends.

Overall, there is general agreement that Arctic sea-ice extent and thickness have decreased during the past several decades. The data are consistent and in agreement with most models. Observations earlier than the late 1950s are sparse in both space and time so that establishing trends beyond the past four decades is difficult.

### Antarctic sea ice

Satellite passive microwave observations have provided the most consistent sea-ice data for the Southern Ocean (Zwally *et al.* 1983, 2002; Gloersen & Campbell 1988; Gloersen *et al.* 1992; Parkinson 1992, 1994, 1998; Johannessen *et al.* 1995; Bjorgo *et al.* 1997; Watkins & Simmonds 2000). Studies prior to about 1998 suggested that there were no significant changes in Antarctic sea ice during the satellite era. However, a systematically calibrated and analysed data set for 1979–98 (Zwally *et al.* 2002) shows that the total extent of Antarctic sea ice (defined as a sea-ice concentration >15%) increased by  $11\,180 \pm 4\,190 \text{ km}^2$  per year ( $0.98 \pm 0.37 \%$  per decade) (Zwally *et al.* 2002). This is in contrast to the decreasing trend ( $34\,300 \pm 3\,700 \text{ km}^2$  per year) for the Arctic, making use of a similarly calibrated and analysed data set (Parkinson *et al.* 1999). Combination of the separate hemispheric sea-ice records into a global record indicates an overall decrease in global sea ice (Gloersen *et al.* 1999). The Antarctic record shows large regional oscillations within the hemisphere so that regional variability and trends are distinct from the hemispherical trends and variability. Regionally, the trends in sea-ice extent are positive in the Weddell Sea, Pacific Ocean and Ross Sea, slightly negative in the Indian Ocean, and strongly negative in the Bellingshausen and Amundsen Seas. Data from the period 1987–96 have also shown that total Antarctic sea-ice extent has increased significantly during this period (Watkins & Simmonds 2000). During the same period, the Antarctic circumpolar atmospheric pressure trough may have both deepened and moved further south (Simmonds *et al.* 1998). Such a shift would have a considerable impact upon the underlying sea-ice distribution through a shift in the net westerly wind regime and subsequent Ekman transport of sea ice (Stammerjohn & Smith 1997).

Thus, as found for the Arctic, shifts in Antarctic atmospheric patterns have an important influence on sea-ice

distribution. Hall and Visbeck (2002) used a coupled ocean–atmosphere model to explore how the SAM generates ocean circulation and sea-ice variations, in the context of the Antarctic Circumpolar Wave (ACW) (White & Peterson 1996; White *et al.* 1998) and the Antarctic Dipole (Yuan & Martinson 2000). A 17-year passive-microwave data set demonstrated that coherent patterns of sea ice show opposite polarities during the two extremes of the Southern Oscillation Index (SOI), and that the climate anomalies in the Bellingshausen/Amundsen and Weddell Sea sectors of the Southern Ocean show the strongest link to the Southern Oscillation (Kwok & Comiso 2002). The composite patterns have been weighted by four strong El Niño–Southern Oscillation (ENSO) episodes over the last 17 years, and these warm events may have weighted the sea ice and climate anomalies towards patterns associated with the negative extremes of the SOI (Kwok & Comiso 2002).

#### Future sea-ice conditions

Global climate models are able to reproduce the observed rates of reduction in Arctic sea-ice extent, and forecasts from these models indicate that reduction in extent will continue to 2025 and beyond. Predictions for future sea-ice distribution vary, but it has been suggested that by 2100 there will be no permanent sea ice in the Arctic (Gregory *et al.* 2002). Aside from the natural physical and environmental impacts, large-scale reductions in Arctic sea-ice extent will enable increased shipping activities in the Arctic, opening trade routes, providing easier access for extraction of resources including oil, minerals and fish, and perhaps leading to increased political tensions between those nations that claim Arctic coastal waters as their own (Kerr 2002).

In the Antarctic, observations of the winter duration of fast sea ice (Murphy *et al.* 1995), inferences from whaling data (de la Mare 1997) and levels of methane-sulphonic acid in an ice core from Law Dome (Curran *et al.* 2003) have all suggested that a step reduction in sea-ice extent and duration occurred sometime between the 1950s and 1970s, before satellite data were available. However, later satellite observations and fast-ice duration records (Fig. 21.4) both indicated a 3–4-year periodicity in the sea-ice field during the 1980s and 1990s (later known as the ACW) (White & Peterson 1996), demonstrating some congruence between the different

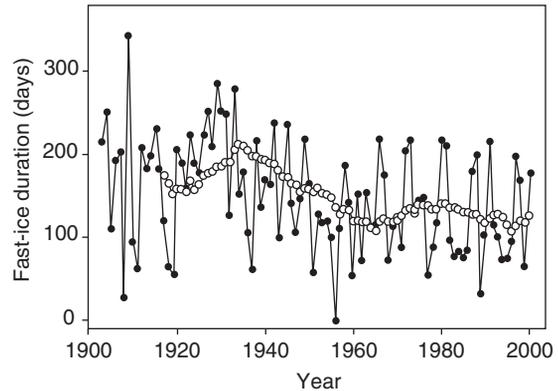


Fig. 21.4. Duration of winter fast-ice at South Orkney Islands. Data for individual years are shown in black, and the clear circles show a tapered 15-year running mean (British Antarctic Survey data, presentation modified from Murphy *et al.* 1995). Data to 1994 were collated from visual observations; data from 1995 were collected using an automatic camera which took four images every day through the winter. Note that the 15-year running mean indicates a period of secular change in mean winter fast-ice duration in the South Orkney Islands from the late 1930s to the late 1960s. This overlaps with, but does not precisely match, the periods of change in sea-ice extent reported from 20° to 30° E using whale catch position as a proxy for the ice-edge (de la Mare 1997), and for East Antarctica using methane-sulphonic acid in the Law Dome ice core to estimate sea-ice extent (Curran *et al.* 2003).

data streams and so providing an additional line of evidence that the inferred step change in Antarctic sea-ice extent was real. Satellite observations have revealed long-term trends in Antarctic sea ice, but the direction of change is not as clear-cut as in the Arctic. On balance, overall Southern Ocean sea-ice extent appears to have increased recently by about 1% per decade (Zwally *et al.* 2002), but this small overall change represents a balance between larger increases in the Weddell, Ross and Western Pacific sectors, and reductions in the Indian Ocean and Bellingshausen–Amundsen sectors. There are few data on Antarctic sea-ice thickness, and no trends have been detected (Murphy *et al.* 1995). Change in Antarctic sea-ice extent to 2025 and beyond is thus difficult to predict because, perhaps counter-intuitively, increased warming may lead to increased snow precipitation and hence to more sea ice.

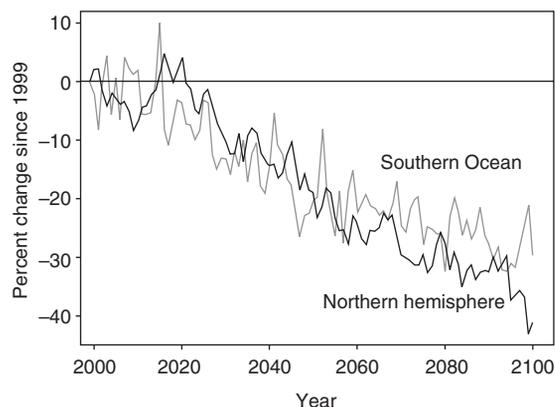


Fig. 21.5. Projected changes in total area of sea ice in the northern hemisphere and the Southern Ocean (Hadley Centre HadCM3 model <http://www.met-office.gov.uk/research/hadleycentre/models/modeldata.htm>).

For both the Arctic and the Antarctic, models suggest a 3% reduction in sea-ice extent by 2025 compared with 2000. For the Arctic, where longer-term observation data are available, this may equate to a reduction of perhaps 14% from the mid-twentieth-century state (see IPCC 2001*a*; Fig. 21.3). The UK Met Office's Hadley Centre HadCM3 model predicts that sea-ice reduction in both hemispheres will continue beyond 2025 (Fig. 21.5). However, because of complex climatic feedbacks that are not incorporated in some models, the reduction is unlikely to follow the sometimes-predicted quasi-linear trajectory over time.

## ECOSYSTEM RESPONSES

### Primary production

The open-water components of polar seas differ markedly in their rates of primary productivity from those that are ice covered. Changes by 2025 in the relative proportions of sea covered with ice will lead to changes in gross polar marine production, but at present it is difficult to predict by how much. For the Arctic, annual pelagic primary production is light-limited, and future reductions in sea-ice extent and duration are expected to reduce shading and increase total annual primary production (Rysgaard *et al.* 1999). This increase will be accentuated because the loss of sea ice will occur predominantly at the periphery of the Arctic Ocean, over the continental shelves (Chapter 19), and production in shelf waters is usually greater than in oceanic waters

(Longhurst 1998). By contrast, in the Antarctic, reduction in sea-ice extent will leave larger areas of less-productive deep ocean uncovered. The boundary between open water and solid pack ice is not abrupt but may span tens to hundreds of kilometres; this marginal ice zone (MIZ) is particularly important for primary production. The MIZ forms as sea ice melts and the pack is broken into smaller floes by wave and wind action. Fresh water released from melting sea ice stabilizes the upper water column, reducing downward mixing, and creates an environment favourable for the development of phytoplankton blooms. Monthly climatological maps of chlorophyll concentration and sea-ice extent derived from satellite observations suggest that mean annual primary productivity in the MIZ has been almost double that in the open ocean (0.66 versus 0.36 g C per m<sup>2</sup> per day). However, because of the relatively small size of the MIZ compared to that of the ice-free pelagic province, the MIZ contributed just 9.5% to the total Southern Ocean production (Arrigo *et al.* 1998).

It is difficult to evaluate by how much the reduction in sea-ice extent by 2025 might reduce MIZ production in the Southern Ocean, because the MIZ is irregularly shaped, highly dynamic and varies in size and position almost daily. Furthermore, recent estimates of annual primary productivity for the Southern Ocean vary by almost an order of magnitude (Smith *et al.* 1998). Complex interactions between position (latitude, underlying ocean depth) and time (irradiance levels vary through the year) will influence levels of production. However, modelling work suggests that as ice extent declines, the MIZ will become located further south earlier in the year and will be less extensive (IPCC 2001*a*). At the same time, there is no linear relationship between loss of sea-ice extent and the loss of MIZ length (length of ice-edge perimeter), and reduction in total production in percentage terms will be much less than the percentage reduction in sea-ice extent. A further complicating factor for the prediction of change in the Southern Ocean is the impact of ozone depletion on the spectral composition of solar radiation at the sea surface. Increased UV radiation (and especially the shorter-wavelength UV-B) may lead to a reduction in MIZ primary production (Smith *et al.* 1992).

### Secondary production

Copepods and other grazers near and in the ice-edge zone in both hemispheres rely on ice-edge phytoplankton blooms to some extent, with numerous species timing their

reproductive cycle to give juveniles optimal feeding conditions associated with the bloom (Conover & Huntley 1991; Kawall *et al.* 2001). The timing of melt, and distribution of ice, can have major impacts on production. Rysgaard *et al.* (1999) suggested that the increased primary production they expect in the Arctic following reduction in sea-ice coverage will lead to increased zooplankton production there. However, if the present situation in a polynya (a region of open water inside an otherwise ice-covered sector) is taken as a proxy for the likely situation in a future ice-free ocean, then the opposite may be inferred. Ashjian *et al.* (1995) found that significant proportions of primary production in the Arctic's North East Water polynya remained unconsumed.

In the Southern Ocean, euphausiids (krill) play a particularly important role in linking primary production to higher predators. Correlative evidence from the western Antarctic Peninsula suggests that reduction in sea-ice extent leads to a reduction in Antarctic krill (*Euphausia superba*) recruitment (see Loeb *et al.* 1997). This is because sea ice provides a favourable feeding habitat for adults, enabling increased reproductive output, and a nursery ground for juveniles (Brierley & Thomas 2002). Multiple seasons of reduced sea-ice extent may lead to reductions in total Antarctic krill population size. The area to the west of the Antarctic Peninsula is a major Antarctic krill breeding zone, and is also an area experiencing major regional warming (King 1994; Vaughan *et al.* 2001); these two factors combined could result in reduced krill biomass by 2025. Overall conclusions, however, are limited by the lack of detailed understanding of the links between ice dynamics and the population dynamics of krill.

In summer, krill appear to be concentrated along the ice edge, rather than being distributed evenly under ice (Brierley *et al.* 2002). As a result, loss of habitat for krill may not occur in proportion to loss of total sea-ice area but may be a function of the loss of ice-edge length. The 25% reduction in ice extent in the 1960s (de la Mare 1997) equates to only a 9% loss of ice-edge length. Changes between now and 2025 are unlikely to be on such a large scale. As with primary production, ozone depletion may impact some elements of secondary production in the Southern Ocean. Naganobu *et al.* (1999) found significant correlations between krill density in the Antarctic Peninsula area and ozone depletion parameters during the period 1977–97. Correlation, though, does not prove cause and effect, and more research is required to elucidate the full range of interactions between krill, sea ice and climate. In

the absence of Antarctic krill, the salp *Salpa thompsoni* sometimes proliferates (Loeb *et al.* 1997). Because salps are not predated upon to a large extent, they may well represent a dead-end in the food chain, and the proliferation of salps has consequences for carbon cycling in the Southern Ocean in that it may divert energy from those areas of the food web leading to predators at higher trophic levels.

### Higher predators

In the Arctic, copepods are predated upon predominantly by fish. The uncertainty surrounding the consequences of environmental change for these predators is illustrated by the conclusion that projected climate change could either halve or double average harvests of any given species (IPCC 2001a). This large range emphasizes the current inability to predict ecological consequences of climate change with any degree of certainty.

A key fish species in the Arctic sea-ice edge ecosystem is the polar cod (*Boreogadus saida*), which could either benefit or suffer from the changed copepod production, following a match or mismatch between spawning and larval food demand (see Pope *et al.* 1994). Changes in abundance of cod will, in turn, affect many seabird and mammal species, since the polar cod is the key link in the Arctic food chain (Legendre *et al.* 1992).

Although the consequences for fish are difficult to infer, the consequences of sea-ice reduction for polar bears seem more clear-cut. Polar bears depend on sea ice as a hunting ground, and reduction in sea ice will lead to a direct reduction of habitat, both in space and time. Bears leave the ice in spring to come ashore to breed. Every week earlier that the bears have to come ashore corresponds on average to a 10-kg reduction in pre-breeding body mass. Thus, as ice melts earlier, bears come ashore in poorer condition and are less likely to reproduce successfully (Stirling *et al.* 1999). As the reduction in sea ice proceeds, the link between the seasonal pack and land could eventually be broken, and it is possible to envisage a situation in the not-too-distant future when bears will be unable to make the transition between breeding ground and feeding ground. Impacts of climate change on polar bears will certainly be site-specific, but climate change may pose a very real threat to some local populations by 2025.

The poleward retreat of sea ice could also break a vital physical link for predators in the Antarctic. Many krill-dependent predators occupy breeding colonies well beyond the seasonal sea-ice maximum, but rely on ocean currents

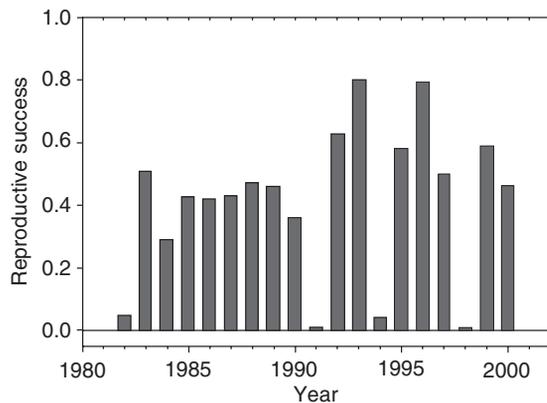


Fig. 21.6. Annual reproductive success of Gentoo penguin (*Pygoscelis papua*) at Bird Island (South Georgia), showing the poor breeding performance in years of low availability of Antarctic krill (*Euphausia superba*): 1982, 1991, 1994 and 1998. The supply of krill to South Georgia is affected by sea-ice conditions along the western Antarctic Peninsula and in the Scotia Sea, and hence is likely to change as the climate warms. (K. Reid, unpublished British Antarctic Survey data 2003.)

and the sea-ice edge to convey krill to them (Hofmann *et al.* 1998). Krill would probably be unable to survive the journey from the Antarctic Peninsula to South Georgia Island across an ice-free Scotia Sea without starving (Fach *et al.* 2002). Krill rely on favourable feeding conditions associated with sea ice, and if the sea ice were to retreat significantly then the essential food source for krill in transit would vanish, and krill would not survive to South Georgia. There is also a correlation between commercial krill catch at South Georgia and the ice-edge position (IPCC 2001a). Significant declines in many krill-dependent penguin, seal and albatross species at South Georgia have already occurred (Reid & Croxall 2001), and changes in the sea-ice environment may in part be responsible for these changes (Fig. 21.6).

Some species at higher trophic levels are able to forage in sectors of the ocean with sea ice ranging from zero to almost total coverage (for example minke whales [*Balaenoptera bonaerensis*]: Thiele & Gill 1999). These will probably be little affected by changes in the sea-ice environment *per se* by 2025. Others, such as emperor penguins (*Aptenodytes forsteri*) suffer if ice extent changes (Barbraud & Weimeskirch 2001), although paradoxically reductions are not always detrimental to all life-history stages. Seabirds are the best-studied vertebrate group in the Antarctic and many recent bird population-level

changes can be attributed to climate change (Croxall *et al.* 2002). A particularly marked example is the poleward shift of breeding distribution of pygoscelid penguins along the Antarctic Peninsula (Fraser *et al.* 1992; R. C. Smith *et al.* 1999; Convey *et al.* 2003). However, evidence of consistent patterns and causal links between ecological responses and climate variability along the western Antarctic Peninsula remains equivocal (Smith *et al.* 2003a, b), and a cautionary note should be adopted with regard to most predictions of the state of sea-ice systems in 2025. Although ecosystem meltdown is a metaphor used often in the popular press in descriptions of the state of the environment or environmental policy (see Bowles 2001; Lean 2003), for ice-edge ecosystems the metaphor may by 2025 transcend polar polemic and be well on the way to reality, with far-reaching consequences for the Earth system as a whole.

### Food web

The discussion above emphasizes that the various parts of the polar marine food web can be expected to respond in different ways to the impact of climate change. The non-linear structure and intense complexity of oceanic food webs make it very difficult to predict how they will respond to environmental change (see review of Clarke & Harris 2003). Prediction is made even more difficult by the fact that both the Arctic and Antarctic oceanic food webs have been disrupted by intense fishing activity.

### FISHING

The two polar regions have had very different histories of impact on their oceanic food webs, largely because of their very different geographies. The Arctic basin is surrounded by indigenous peoples who harvested the seas for millennia; the Southern Ocean is hostile and a long way from the populated part of the world, and consequently has been fished only relatively recently.

### Harvesting of Arctic marine resources

Harvesting of marine living resources, including fish and marine mammals such as seals and whales, is vital to the sustenance and culture of Arctic peoples, and the Arctic is also one of the world's most important international fishing grounds. In the past, many Arctic marine mammals were overexploited (Pagnan 2000), and many are still considered globally endangered, for example bowhead (*Balaena*

*mysticetus*), sei (*Balaenoptera borealis*), blue (*B. musculus*), fin (*B. physalus*) and northern right whales (*Eubalaena glacialis*) and Steller's sea lion (*Eumetopias jubatus*) (CAFF [Conservation of Arctic Flora and Fauna] 2001). Numerous other species present in the Arctic have been classified as globally vulnerable. Many of these species appear to be in decline in certain Arctic localities, although at others they appear stable or sometimes increasing; more generally however, there is a lack of data to determine overall trends (CAFF 2001).

New technologies and commercial fisheries have increased the scale of fish catches in Arctic regions. Historically, overharvesting has led to the localized collapse of numerous Arctic fish stocks, including herring (*Clupea harengus*), cod (*Gadus morhua*), whitefish (*Coregonus* sp.) and capelin (*Mallotus villosus*) (UNEP [United Nations Environment Programme] 1999b; Huntington 2000; Pagnan 2000; Northeast Fisheries Science Center 2002). While there is evidence of some recovery, not all stocks have recovered, and harvesting pressure remains high in some areas (Pagnan 2000). Moreover it has proved difficult to determine unequivocally the cause of decline, because for some species the effects of fishing pressure on stock size are confounded by climatically driven variability (OSPAR Commission 2000b). There is a high level of natural variability in Arctic fish stocks, suggesting that for the fishery to be sustainable, catch levels should be set more conservatively than has often previously been the case.

### Harvesting of Antarctic marine living resources

Although harvesting of Antarctic marine living resources started long after that of the Arctic, fishing within the Southern Ocean also has a long history. In the eighteenth century, an active fishery for southern fur seal (*Arctocephalus gazella*) developed; the first sealers reached the Antarctic in 1778, and by 1791 over 10 million skins had been taken. Exploitation was initially at South Georgia, but soon moved to the South Shetland Islands as these stocks were depleted. By 1822, after only 35 years, the southern fur seal was almost extinct, and the industry collapsed (Bonner 1982).

The large numbers of great whales found in the Southern Ocean had also not escaped notice, and exploitation soon shifted to these. The first land-based whaling stations were established at South Georgia in 1906, but the critical innovations were the invention of the steam

harpoon gun and the development of pelagic whaling ships (Headland 1984). The peak of whaling activity came between the two world wars, and by the mid 1960s the industry had collapsed economically, although significant unregulated whaling of protected stocks also took place subsequently, and some residual fishing for minke whales continues. In the first half of the twentieth century, taxes levied on whale products were used to fund the *Discovery* investigations based at South Georgia (Hardy 1967). Although concerned primarily with understanding the biology of the great whales being exploited, these pioneering studies provided the most comprehensive investigations of the biological oceanography of the Southern Ocean yet undertaken. In particular, they included a major study of the biology of *Euphausia superba*, a pivotal organism in the Southern Ocean ecosystem, and a major prey species for many fish, squid, seabirds and marine mammals.

In the late 1960s, attention switched to finfish, and in less than 5 years the stocks of marbled rockcod (*Nototothenia rossii*) at South Georgia were reduced to uneconomic levels, from which they are recovering only slowly. The fishery then moved to new locations and species, notably icefish (*Champsocephalus gunnari*) (Kock 1992). The present fishery is directed at Patagonian toothfish (*Dissostichus eleginoides*), using bottom-set long-lines. In the 1970s, a trawl fishery for Antarctic krill was also developed. This was based principally around South Georgia in winter and the ice-free regions of the Scotia Sea in summer (Everson 2000). Experimental krill fishing was undertaken by eight nations in the 1970s (Agnew & Nicol 1996), prompted in part by the possibility that the decrease in the populations of krill-eating higher predators (notably baleen whales and fur seals) through fishing activities might have resulted in a krill surplus. The Southern Ocean food web is, however, complex and non-linear, and this makes the response of the system to fishing pressure very difficult to predict (see e.g. Clarke & Harris 2003).

The total catch of krill increased during the late 1970s to a maximum of over 500 000 tonnes in 1982; the current annual catch is of the order of 100 000 tonnes (Agnew & Nicol 1996). The original Antarctic Treaty, which applies south of 60° S latitude, made no attempt to regulate or manage fisheries. In the early 1970s, concern over possible environmental effects of overfishing led first to the most important series of international oceanographic studies since the *Discovery* investigations, the BIOMASS programme of the Scientific Committee for Antarctic

Research (SCAR). This was followed by the development and ratification of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR). This Convention is now responsible for the regulation of all Southern Ocean fisheries (excluding exploitation of mammals such as whales and seals, which are covered by separate conventions). The CCAMLR area is different from that of the Antarctic Treaty, applying as it does to a region that is broadly coincident with the Southern Ocean as defined by the Polar Front, and including islands such as South Georgia and Kerguelen.

CCAMLR was the first such fisheries-management regime to take a holistic ecosystem-based view (Constable *et al.* 2000). Explicit attention is directed at the effects of a given fishery on the rest of the system, and specifically on the dependent predators. To monitor any such impact requires information on both harvested and dependent species, their interactions and the manner in which their populations vary naturally in size (Everson 2002). A key mechanism for achieving this is the CCAMLR Ecosystem Monitoring Programme (CEMP), which uses data from selected higher predators to monitor the upper trophic levels of the Southern Ocean marine ecosystem (Agnew & Nicol 1996; Constable *et al.* 2000; Everson 2002). This holistic approach may enable successful ecosystem management to be implemented even in the face of changes that may be manifest by 2025.

### IUU and seabird bycatch

The major fisheries-related threats to the Southern Ocean ecosystem currently come from illegal, unreported and unregulated fishing (IUU) together with the impacts on seabirds feeding outside the Southern Ocean (Kock 2001). Although the fishery for Patagonian toothfish within the CCAMLR area is regulated, there is overwhelming evidence of significant IUU activity. For example, even minimum estimates of the IUU catch indicate that around one-third of Patagonian toothfish taken within the CCAMLR area in the late 1990s was from IUU fishing (Lack & Sant 2001). Whilst the absolute level of IUU catch is uncertain, what is clear is that it constitutes a significant issue for the Patagonian toothfish fishery and for CCAMLR (Collins *et al.* 2003).

The other area of great conservation concern is the mortality of seabirds (specifically albatrosses and larger petrels), which are killed in long-line fisheries outside the Southern Ocean. This mortality is leading to a severe

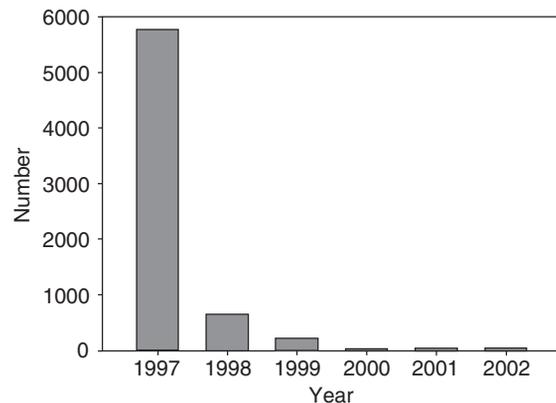


Fig. 21.7. Seabird by-catch in the licensed CCAMLR (Convention for the Conservation of Antarctic Marine Living Resources) fishery for Patagonian toothfish (*Dissostichus eleginoides*) at South Georgia. By-catch decreased significantly following the implementation of CCAMLR conservation measures. Note that seabird by-catch remains high but unquantified in the IUU (illegal, unreported and unregulated) fishery and thus continues to be a major conservation concern. (Data from Croxall & Nicol 2004.)

decline in all albatross populations (Croxall *et al.* 1997; Gales 1997), and is currently an area of very great scientific, conservation and public concern. A new international Agreement on the Conservation of Albatrosses and Petrels was concluded in 2001 under the Convention on the Conservation of Migratory Species of Wild Animals, although only seven nations were party to its agreement (New Zealand, Australia, Brazil, Peru, Chile, France and the UK). With numerous key fishing countries yet to sign up, it is too soon to assess this agreement's practical effect. However, it is clear that whilst implementation of guidelines for reducing seabird by-catch has significantly reduced incidental mortality within the CCAMLR-regulated fishery (Fig. 21.7), such mortality within the IUU fishery remains a major conservation concern.

## THE POLAR MARINE ECOSYSTEMS IN 2025

Detailed prediction is impossible, but a general picture can be provided of how the two polar marine ecosystems might look in 2025.

Current climate warming is expected to continue, with consequences for the volume and dynamics of sea ice.

In the Arctic, less-extensive sea ice and a further extension of the summer open-water period are expected. For the Antarctic, a continued small overall increase in sea ice is likely, although with marked spatial variability. In particular, sea ice in the Bellingshausen and Amundsen Seas may continue to decline, associated with continued regional climate warming of the Antarctic Peninsula. Polar ecosystems are dominated by ice, and the narrow temperature threshold for an ice-to-water phase change may create a pronounced non-linear response to what is a relatively small temperature shift. Consequently, such non-linear amplifications of small climatic changes may increase the ecological response and amplify trends or change (Smith *et al.* 2003a; Welch *et al.* 2003).

It is likely that the change in extent and timing of ice cover will affect the intensity of primary production, although it is difficult to predict the overall quantitative impact, or the synergistic effect of enhanced UV flux from the springtime reduction in high-latitude ozone. Impacts on intermediate levels of the food web (zooplankton and nekton) remain largely unknown, although continued changes to sea-ice dynamics in the western Antarctic Peninsula region may affect the abundance of Antarctic krill, and there may be significant changes to the distribution of ice-associated higher predators.

The effects of climate change on the two polar marine ecosystems are likely to be substantial and far-reaching, and these could be exacerbated by the direct human effects through localized pollution or unregulated exploitation of living resources. Climate change is likely to lead to a very different polar ecosystem in 2025, although it is presently difficult to predict the magnitude, timing or distribution of many of the anticipated changes. For some iconic species, such as the polar bear, the consequences may be particularly severe.

There is, perhaps, some cause for cautious optimism when it is considered that the world's nations were capable of collectively agreeing to limit the production of ozone-destroying chemicals within just two years of the discovery of conclusive evidence for the damage they were doing to the Antarctic ozone layer (Farman *et al.* 1985). Balanced against this, however, should be remembered that even where concerted international action was taken, the 2003 ozone hole became the most extensive on record, and the world will suffer at least four more decades of ozone destruction before the system is expected to return to its original conditions. However, observed ozone depletion and climate change have also shown complex and incompletely understood linkages. Consequently, these assessments and predictions must be viewed within the context of continuing environmental change.

In the case of climate change, the situation is substantially more complex and difficult to predict, and there is an urgent need for more research to elucidate the mechanisms driving changes and to improve models as the basis for prediction. In the light of the uncertainties, which themselves are often used effectively to avoid taking corrective actions, the potential for unanticipated changes and possibly even more severe consequences should not be forgotten. Given the scale of the changes that the evidence seems to show are afoot, the case for more precautionary approaches to the management of human activities certainly can be made. There is now an urgent need to build actions into effective international agreements, such as those that address the more localized impacts of exploitation, for example through sustainable fisheries regimes, and those that address the more global changes, for example through the Kyoto Protocol. If the latter cannot be accepted by all key governments, then it is imperative that a viable alternative be found.