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# Polar marine ecosystems: major threats and future change

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## SUMMARY

**This review of polar marine ecosystems covers both the Arctic and Antarctic, identifying the major threats and, where possible, predicting their possible state(s) in 2025. Although the two polar regions are similar in their extreme photoperiod, low temperatures, and in being heavily influenced by snow and ice, in almost all other respects they are very different. The Arctic Ocean is a basin surrounded by continental land-masses, close to, and influenced by, large populations and industrial activities. In contrast, the Southern Ocean is contiguous with all the other great oceans and surrounds a single land mass; Antarctica is remote from major centres of population and sources of pollution. Marine environments in both polar regions have been highly disturbed by fishing activity, but, in terms of pollution, some areas remain among the most pristine in the world. There are, however, both local and global pressures. Over the 2025 time horizon, the greatest concern for the Arctic is probably the ecological implications of climate change, particularly insofar as sea ice extent and duration are likely to be affected. Such changes are not expected to be as pronounced in the Southern Ocean over this time period, and concerns are related more to direct threats from harvesting of marine living resources, and the ability to manage these fisheries sustainably. In both polar regions, the capacity of marine ecosystems to withstand the cumulative impact of a number of pressures, including climate change, pollution and overexploitation, acting synergistically is of greatest concern.**

*Keywords*: Arctic, Antarctic, oceanography, climate change, biological impacts, ozone depletion, pollution, circumpolar current, polar marine ecosystems

## INTRODUCTION

Both the Arctic and Antarctic are at high latitudes and thus subject to an extremely seasonal photoperiod; they are also both cold environments, influenced heavily by snow and ice. In almost all other respects, however, the two polar regions are very different. Topographically they are almost mirror images of one another. The Arctic Ocean is a basin surrounded almost completely by continental land masses, whereas the Southern Ocean is contiguous with all the world's great oceans and surrounds a single isolated land mass. The two polar oceans thus differ significantly in their proximity to centres of population and sources of pollution, and in their history of human influence.

The aim of this review is to assess the current threats to polar marine ecosystems and, where possible, predict their possible state in 2025. Because the Arctic and Southern Ocean marine ecosystems exhibit more differences than they do similarities, we will deal with them separately. We will, however, attempt to draw some general conclusions at the end.

The Arctic environment has recently been subject to a comprehensive review through the mechanism of the Arctic Monitoring and Assessment Programme (AMAP 1997, 1998) of the Arctic Council. This review of both polar ecosystems draws substantially on AMAP findings, although with the added dimension of a comparative analysis with the far more limited information available (at least in collated form) for the Southern Ocean. There is as yet no comparable report examining the state of the Antarctic environment, although a recent report on the Ross Sea region (Waterhouse 2001) is an excellent first step.

## THE ARCTIC MARINE SYSTEM

The Arctic (Fig. 1) may be defined in numerous ways depending on the purpose. For example, a definition in everyday use is the area north of the Arctic Circle (66° 32' N). Polar ecosystems are however related more to climate than a line of latitude, and for this reason the 10°C July isotherm has often been used to define the southern limit of the Arctic (Fig. 2). Other definitions, such as the northern tree line, or the line of southernmost continuous permafrost, have also been used. The Arctic Polar Front is often regarded as defining the southern boundary of the Arctic marine environment. This is the zone where colder, less saline surface waters in the north meet warmer and more saline water from the south (Fig. 2). The boundary selected for the present review corresponds to that used for the Arctic Monitoring and Assessment Programme (AMAP 1997, 1998), which used a

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**Figure 1** Arctic features and places referred to in the text.

combination of environmental, geographical and political criteria to define a practical limit to the area of interest. This boundary includes some marine areas south of the Arctic Polar Front.

As defined above, the Arctic marine ecosystem covers an area of approximately 20 million km$^2$. Permanent sea ice covers 40% of this area year-round, while at the winter maximum (March–May) this expands to approximately 75% (Fig. 3). This variation in sea ice cover results from dramatic seasonal changes in solar radiation and air temperatures. Air temperatures over pack ice drop to around −30°C during winter, while in summer over the permanent ice they generally range between −10°C and +10°C. In lower latitudes and over land in summer, however, temperatures may reach +30°C. Seasonal variance in seawater temperatures is however more modest, with the Arctic Ocean remaining near freezing year-round, while seas over the extensive continental shelf areas may vary from –1.9°C in winter to +5°C during summer. Seawater in the Atlantic and Pacific regions experiences the greatest variability and here the temperature generally remains above 0°C throughout the year (AMAP 1997).

The Arctic is strongly influenced by the dominant regional patterns of atmospheric and oceanic circulation. These circulations are driven by latitudinal temperature gradients and generally function as poleward heat transfer mechanisms. Thus, relatively warm air and water masses circulate toward the Arctic from the lower latitudes, while colder Arctic air and water are transferred southwards. The time scales of the transfers are very different between atmosphere and ocean systems, being measured in days in the former and years in the ocean. The surface Arctic oceanic circulation is dominated by the Transpolar Drift and the Beaufort Gyre, the former transporting water and sea ice across the Arctic Ocean from the Bering Strait (between Alaska and Russia) and out through Fram Strait via the East Greenland Current (Fig. 4). The Beaufort Gyre circulates clockwise within the Beaufort Sea, north of Alaska and the Canadian Arctic Archipelago. Ocean inflow is predominantly via the North Atlantic Current, moving at depths of 200–1700 m beneath the less saline and less dense Arctic surface water, principally through the Fram Strait and Barents Sea region. Inflow is also from the Pacific through the Bering Strait at depths of 50–200 m. Rivers contribute

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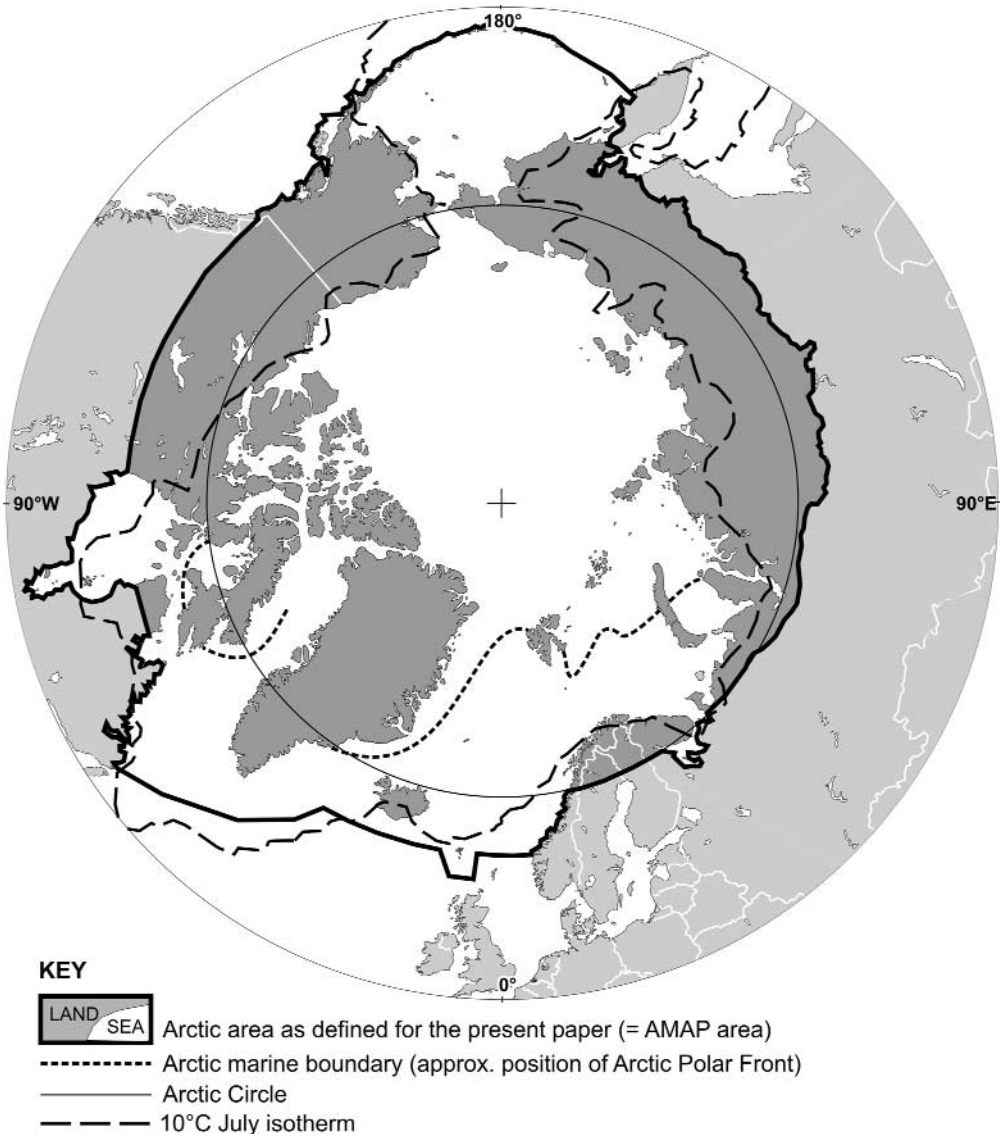



**Figure 2** Arctic geographical and environmental boundaries (modified from AMAP 1998, p. 9).

some two per cent of water input to the Arctic Ocean (Sugden 1982) and help to reduce surface salinity, especially at spring thaw which accounts for approximately 80–90% of the yearly total run-off (AMAP 1998).

## Environmental forcing factors in the Arctic marine system

Pressures on the Arctic marine ecosystem are derived from both global and local sources (Table 1). Pollutants generated in Europe, Asia and North America are transported very effectively into the Arctic environment by the atmospheric and oceanic circulation processes noted above. These include persistent organic pollutants (POPs) from industrial and agricultural practices (e.g. metal smelters, paper and waste processing plants, pesticides, herbicides), heavy metals (e.g. lead from petrol), and radionuclides (e.g. emissions from reprocessing plants such as Sellafield in the UK, and accidents such as Chernobyl in Russia).

POPs, such as polychlorinated biphenyls (PCBs), hexachlorocyclohexane (HCH), hexachlorobenzene (HCB), dioxins, and various other biocides (e.g. DDT, chlordane, toxaphene), are typically long-lived in the environment and often highly toxic even in small quantities (AMAP 1998). Marine organisms may take up POPs, which have a tendency to accumulate, particularly in fatty tissues, with concentrations often increasing at higher levels in the food chain. Some Arctic indigenous ethnic groups, which rely heavily on food from species at high trophic levels in both marine and terrestrial ecosystems, show levels of POPs in tissue and breast milk significantly higher than those found in more southerly populations (AMAP 1998).

Sulphur compounds generated in mid-latitude industrial areas are transported northward and deposited as acid rain in Arctic regions, and high atmospheric particulate levels combined with cold temperatures have led to 'Arctic haze' (Shaw 1975, 1995; Ottar *et al.* 1986; Rahn 1989; AMAP 1998). Northward-flowing rivers are other important pathways for

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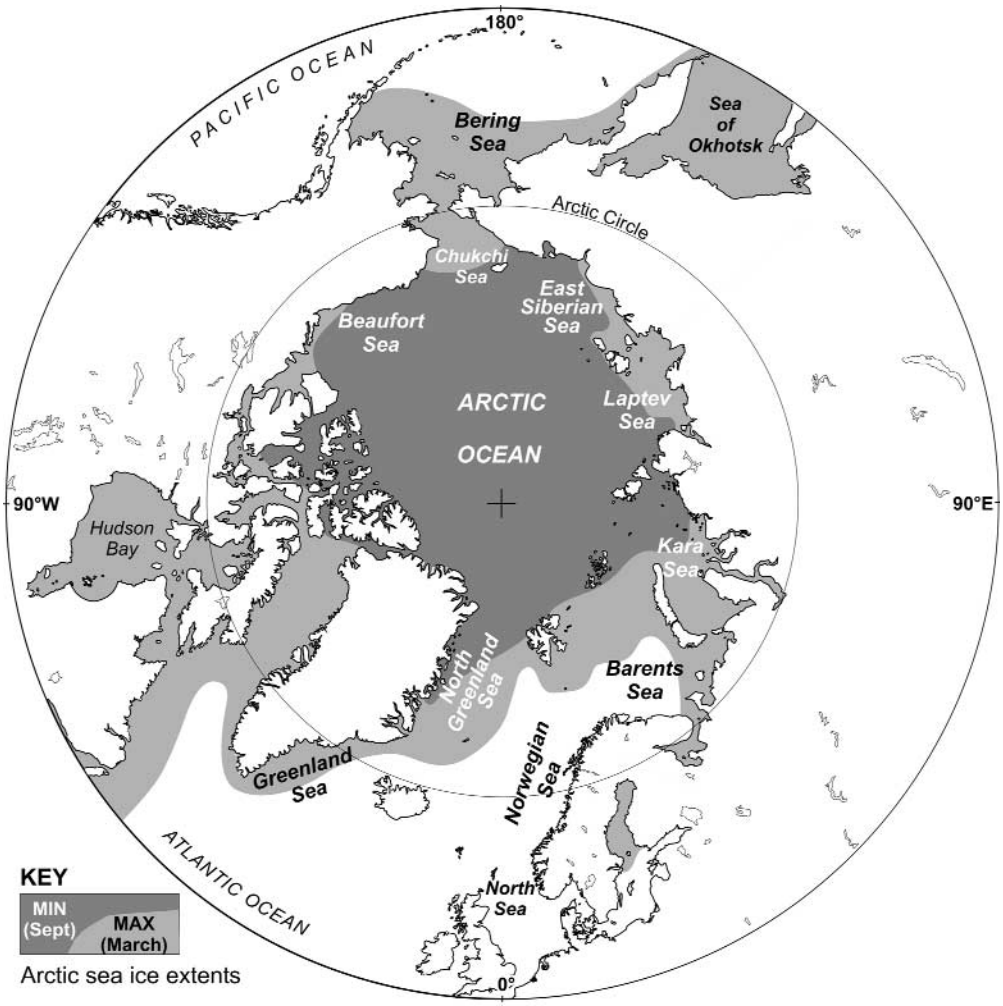



**Figure 3** Average maximum/minimum sea ice extent in the Arctic (modified from AMAP 1998, p. 65).

pollutants from the lower latitudes into the Arctic marine environment, with characteristic pulses when accumulated contaminants are released from winter ice and snow in the spring thaw (AMAP 1998). In addition, sea ice may accumulate pollutants, and transport and then discharge them at the principal melt-points.

Local sources are also significant for certain forms of pollution within the Arctic marine environment. For example, for many years the Arctic Ocean was used by the former Soviet Union for nuclear testing and as a dumping ground for radioactive wastes, particularly in the Barents and Kara Seas. Substantial contamination by heavy metals has originated from industry and mining in the Russian Arctic. POPs have originated from military installations, industry, waste disposal and pest control practices in the Arctic. Oil and gas extraction is a substantial Arctic industry, and pollution arising from accidents is not uncommon in the harsh conditions. Pressures on Arctic fish stocks originate both from large-scale commercial fisheries operating in the region, as well as from smaller-scale local use.

## Environmental trends in the Arctic marine ecosystem

*Persistent organic pollutants (POPs)*

All of the main forms of POPs have been detected in the Arctic, although generally levels are lower than in more temperate regions (AMAP 1998). Regional patterns are evident in the levels of different forms of POPs. For example, the highest HCH levels in surface seawater have been observed in the northern Canadian Arctic Archipelago (AMAP 1998, p.256), while the highest PCB levels are observed in the coastal areas of the Kara and Laptev Seas (Crane *et al.* 2001). HCH is believed to have been trapped by ice and currently observed levels reflect higher atmospheric levels of this pollutant from about 15–20 years ago, while PCB levels result from higher contemporary inputs from Russian rivers. HCH levels are expected to decline as the more highly contaminated ice is exported out of the system (AMAP 1998, p.257), although it is likely to take decades for the upper ocean to be cleared (Macdonald *et al.* 2000). While atmospheric contributions of HCH have been substantially reduced (Macdonald *et al.* 2000), recent analyses indicate higher HCH inputs to the Arctic Ocean from Russian rivers

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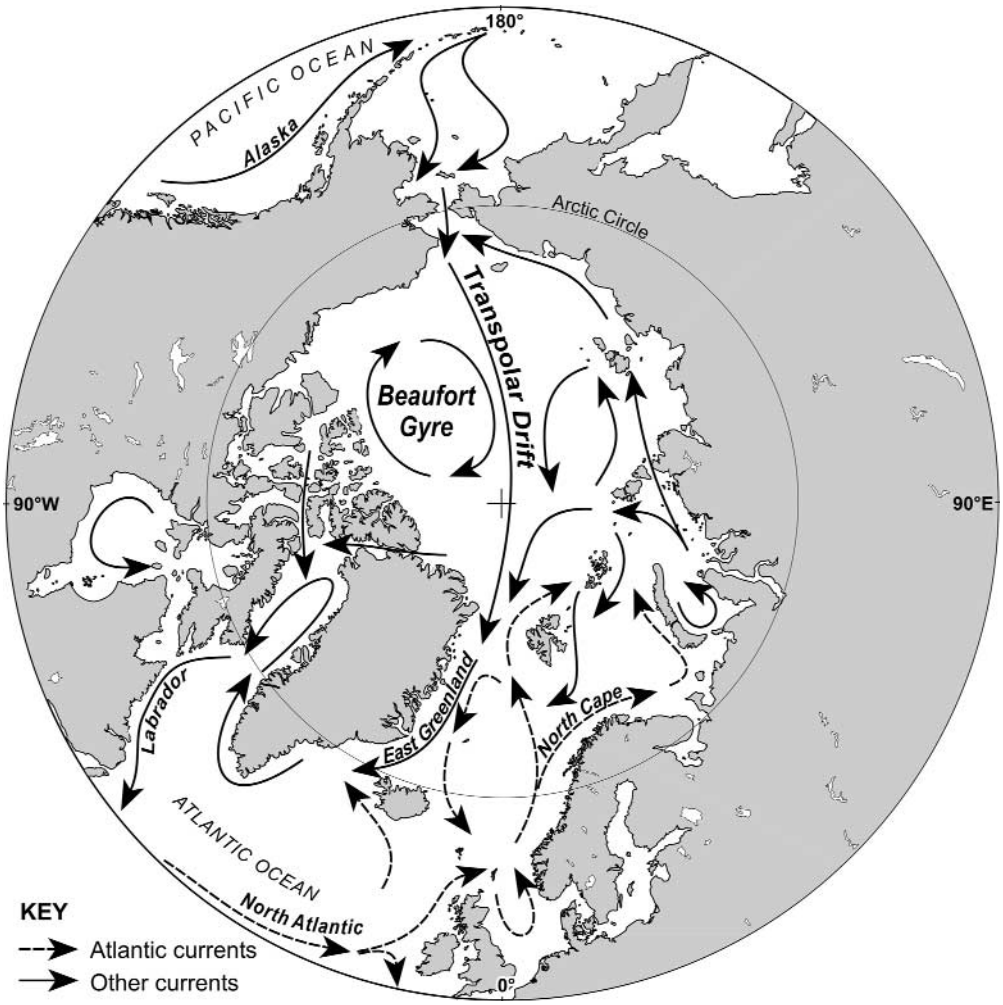



**Figure 4** The major Arctic oceanic circulation patterns (modified from AMAP 1998, p. 23).

than previously thought (Alexeeva *et al.* 2001), which may prolong the period of anticipated reduction. Despite reduced input for several decades, as yet there is little evidence of reduced PCB loadings in the Canadian Arctic, and it is anticipated that reductions in these contaminants will also take several decades (Macdonald *et al.* 2000).

Biomagnification of POPs in the Arctic marine ecosystem is a significant concern, as illustrated in the elevated PCB levels found in Arctic marine organisms (Fig. 5; AMAP 1998). There is also a distinct geographical trend, with the highest levels in seals being observed in northern Norway, Svalbard and Russia. POPs are known to have negative effects on animal immune, reproductive and endocrine systems, and the levels observed are generally above those at which no biological effects could be expected. While levels in Russia are still largely unknown, overall the data suggest that most POP species are decreasing in concentration (AMAP 1998).

*Heavy metals*

Mercury, cadmium and lead pose the greatest concerns in relation to heavy metal pollution in the Arctic environment (AMAP 1998; Macdonald *et al.* 2000). These metals are all present naturally in the Arctic, although both global and local human sources (e.g. from fossil fuels combustion, mining and wastes) have raised concentrations in some areas to levels that pose risks to the environment and biota. Emissions of greatest concern come from point sources, particularly from large mines and industrial processing plants in the Kola Peninsula, Pechora Basin, Urals, Noril'sk and Yakutsk regions of the Russian Arctic (Fig. 1; AMAP 1998). Several mines in Greenland have also contaminated local marine ecosystems (Johansen *et al.* 1985), and although high levels of heavy metals have been recorded, actual biological impacts have yet to be documented (AMAP 1998). More generally, however, the levels of mercury, cadmium and lead in Arctic freshwater and marine systems remote from the point sources are similar to those at unpolluted areas elsewhere, at levels $<1\ \mu g\ l^{-1}$ (AMAP 1998, p. 417). The highest concentrations of heavy metals in surface seawater tend to occur along the Russian Siberian coast (Crane *et al.* 2001).

Analyses of Greenland ice cores show a sharp increase in the deposition of these three metals since 1850 through to about 1980, although subsequently there has been a

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**Table 1** Principal environmental forcing factors and impacts on the Arctic marine ecosystem. Environmental forcing factors are considered in this paper as pressures responsible for driving change.

| *Key sources* | *Environmental forcing factors* | *Magnitude of pressures and principal impacts* |
|---|---|---|
| Global (industrial pollutants, waste disposal, pesticides, herbicides) and local (relatively minor) | POPs | Levels generally low and decreasing, although with local 'hot spots'. Taken up in foods, with bioaccumulation and biomagnification. Negative impact on immune, endocrine and reproductive systems. Some known carcinogens |
| Global (burning fossil fuels) and local (mineral resource extraction and processing, waste disposal) | Heavy metals | Widespread but generally low background levels; locally severe near metal processing facilities and mines, particularly in Russian Arctic. Levels typically decreasing, with exception of mercury. Biological impacts in marine environment not yet documented |
| Global (burning fossil fuels, industrial pollutants, ore processing) | Acid rain and sulphur deposition | Widespread and locally severe impacts in Arctic freshwater environments, although marine ecosystem relatively unaffected |
| Local (mineral resource extraction) | Oil and gas extraction | Oil spills such as *Exxon Valdez* killed large numbers of seabirds and marine organisms. Other large spills in Russian Arctic have affected river systems. Otherwise, significant spills in Arctic marine environment have not yet occurred |
| Global (nuclear testing, accidental releases) and local (testing, dumping, accidents, construction, mining) | Radioactivity | Atmospheric nuclear weapons testing discontinued but of greatest impact, with an estimated 750 additional cases of human cancer in Arctic peoples owing to fallout. Chernobyl accident detectable in Arctic, though levels low. Releases from Sellafield detected in Arctic, though levels low. Local contamination at specific sites may be high, but overall impacts on marine ecosystem seem low |
| Global (burning fossil fuels, industrial pollutants, forestry and agricultural practices) | Climate change | Some evidence for significant change in sea ice extent and thickness in Arctic Ocean, although spatial pattern of changes non-uniform. Impacts on ecosystem poorly known, although potentially substantial |
| Global (industrial pollutants) | Ozone depletion | Moderate depletion in Arctic, although increasing. Impacts on marine ecosystem unknown, believed to be relatively minor at present |
| Local (marine living resource extraction) | Fishing | Fishing in Arctic Ocean has reduced severely stocks of some fish, and some marine mammals. Fish stock recovery variable |

substantial decline in snow surface concentrations (Boutron *et al.* 1995; Candelone *et al.* 1995). This suggests improvements in emission controls and/or output reductions (AMAP 1998, p. 403). Remote from point sources of pollution, lead levels in the marine environment are generally low and similar to current global background levels, which are more than 10 times prehistoric levels (AMAP 1998, p. 417). Cadmium in Arctic seawater is also considered to be close to natural background levels, and levels in marine sediments reveal no temporal trends (AMAP 1998; Macdonald *et al.* 2000). On the other hand, there is evidence that mercury levels are increasing in Canadian and Finnish Arctic lakes (AMAP 1998, p. 413). It is thought that the relative mobility of mercury and the cold Arctic air favour deposition of this metal in the region. Mercury levels in the Arctic Ocean, however, remain low (Weiss *et al.* 1974; AMAP 1998).

In marine biota, lead levels are generally low, and there is little evidence of bioaccumulation or biomagnification of this metal in the Arctic (Norheim *et al.* 1992; Dietz *et al.* 1996; Wagemann *et al.* 1996). This is not the case for cadmium, however, which shows elevated levels with increasing age in marine mammals and birds and at the upper levels in food chains, such as for seabirds, seals, whales and polar bears (AMAP 1998). Levels in some cases are greater than those at which kidney damage in some animals could be expected, although studies to date have not documented such damage (Dietz *et al.* 1998). Levels appear to be highest in marine animals from north-eastern Canada and north-western Greenland. Elevated levels of mercury in marine animals have also been observed, with ringed seals from the western Canadian Arctic showing levels of up to 219 $\mu g\,g^{-1}$ in the liver (Wagemann *et al.* 1996), and the highest levels (280 $\mu g\,g^{-1}$) in the livers from pilot whales in the Faeroe Islands (Julshamn *et al.* 1987). While levels may be high, the high natural presence of selenium in the Arctic may be acting to neutralize some of the toxic effects, and the actual impacts are more difficult to determine.

### *Acid rain and sulphur deposition*

Acidification has a long history in the Arctic (Simões & Zagorodnov 2001) and significant damage was observed in

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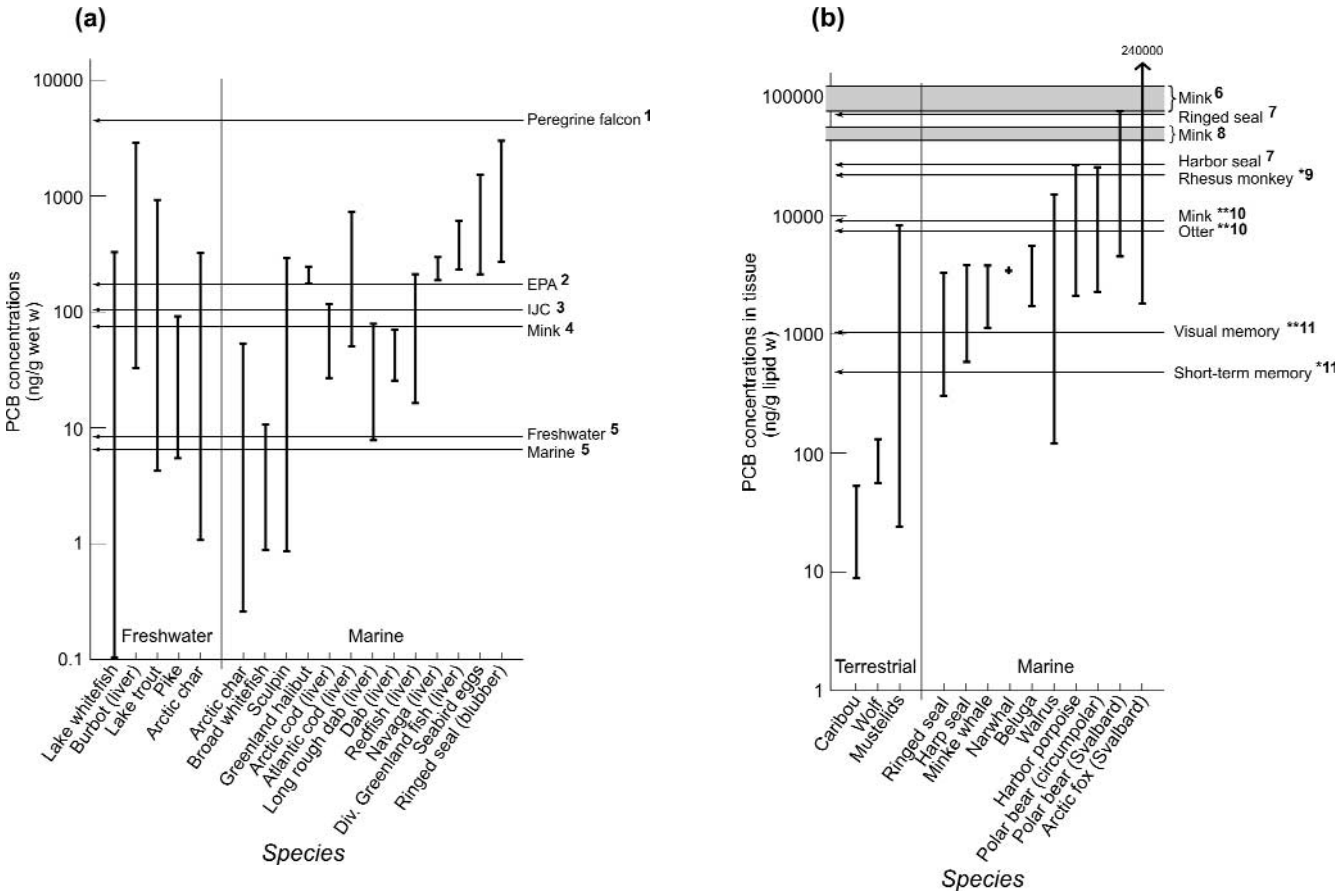



**Figure 5** PCB levels in Arctic marine organisms: (*a*) Ranges of mean ΣPCB (ng $g^{-1}$ wet weight) in Arctic prey species compared to no-effect concentrations and environmental quality guidelines for protecting fish-eating/aquatic wildlife, and (*b*) ranges of mean ΣPCB (ng $g^{-1}$ lipid weight) in tissue of Arctic mammals compared to thresholds for mammalian effects (modified from AMAP 1998, pp. 296–97, Figs. 6.61 and 6.63). 1. Highest no-effect concentration in food; 2. Guideline adopted by US Environmental Protection Agency; 3. Guideline adopted by International Joint Commission; 4. Highest no-adverse-effect concentration in food; 5. Canadian Environment Agency guidelines; 6. Effective concentration causing a response in 50% of treated organisms (EC50), kit survival, liver; 7. Poor reproductive success; 8. EC50, litter size, liver; 9. Immune effects, blood; 10. Kit survival or poor reproductive success, muscle; 11. Human offspring, cord blood serum; * Lowest observed effect level; ** No observed effect level, or no observed adverse effect level.

Norwegian aquatic ecosystems (as indicated by fish deaths) as early as 1911 (AMAP 1997). Similar observations were made in other Arctic countries in the 1960s, and it was established that the high levels of sulphuric acid in rainwater causing the damage were principally originating in Europe, North America, eastern Asia and China (Sturges 1991; Benkovitz *et al.* 1996; Shaw 1995). The contamination has been mainly in the form of sulphur dioxide released by industrial activities, burning of fossil fuels and the processing of metal ores. The formation of 'Arctic haze' is a photochemical reaction resulting from the winter build-up of sulphur and its reaction with atmospheric oxygen compounds (ozone, hydroxyl radicals, peroxide) at the return of spring sunlight (Shaw 1995; AMAP 1998). Recently emissions from Europe and North America have been reduced with implementation of stricter controls through agreements such as the Convention on Long-Range Transboundary Air Pollution (LRTAP), and moves toward cleaner technologies. However, in Russia, the LRTAP Convention may have merely redistributed the problem rather than substantially reducing it. Some heavily polluting industries close to western borders were relocated to Siberia in order to comply with the convention because it is based on transboundary movements of pollutants rather than national emissions (Kotov & Nikitina 1998*a*).

Within the Arctic itself, the most significant sources of the pollution are from the metals-processing industries, particularly in the Kola Peninsula and Noril'sk regions of northern Russia. The company Noril'sk Nickel accounts for approximately one-tenth of the total air pollution from stationary sources in Russia and is Russia's largest polluter (Kotov & Nikitina 1998*b*; AMAP 1998). Emissions from industries in Noril'sk contribute *c.* 1.9 Mt of air pollutants to the atmosphere annually, about 92% of which are in the form of sulphur dioxide. Approximately 144 000 tonnes of air

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pollutants were released in the Kola Peninsula region in 1994, or about 84% of regional emissions (Kotov & Nikitina 1998*b*). In 1991, about 8100 ha of land had been damaged beyond repair on the Kola Peninsula, while in north-eastern Siberia some 180 000 ha of forest have been destroyed and a further 382 000 ha damaged. Thus, the scale of damage from local sources is large, at least in terrestrial areas.

The effects of acid deposition on the Arctic aquatic environment are influenced by the highly seasonal nature of the hydrological system. In Arctic streams, for example, the first 20% of spring meltwater can contain up to 80% of the acidic cations, increasing average concentrations by up to four times (AMAP 1998). Watercourses and lakes close to the major industrial centres in the Arctic are those most strongly affected. Springtime acidity in some water bodies is high enough to cause concern for some species of fish, in particular brown trout (*Salmo trutta*) and salmon (*Salmo salar*) (AMAP 1998, p. 650). However, more generally, significant widespread declines in freshwater species as a result of acidification have not recently been reported, and except for areas in close proximity (within 200 km) to heavy industries; there is no evidence that it is a problem on an Arctic-wide scale today (AMAP 1997). The Arctic marine environment, with its high buffering capacity, is not expected to have been significantly affected.

*Oil and gas extraction*

The Arctic is a significant region for oil and gas extraction and many of the activities are taking place within or adjacent to aquatic environments. The principal regions of production and exploration are Alaska's North Slope and Prudhoe Bay, the northern Mackenzie River in Canada, the Norwegian Sea, the Barents Sea and northern Siberia (Fig. 1; AMAP 1998, p. 662). Risks to the marine environment are both chronic and acute, mainly from spills, which can have a devastating impact on the ecology. For example, the *Exxon Valdez* tanker spilled 35 000 tonnes of oil into Prince William Sound, Alaska, in 1989. Although estimates vary, up to 500 000 seabirds may have been killed (Piatt *et al.* 1990; Piatt & Ford 1996), as well as many sea otters, seals, whales and smaller marine organisms. In 1994 at Usinsk, Republic of Komi (Siberian Arctic), approximately 40 000 tonnes of oil were spilled into the tundra and watercourses leading to the Pechora River (Fig. 1). Although most of the oil was prevented from reaching the Pechora River, the total including spills from the associated pipeline has been estimated to have been over 100 000 tonnes (Melnikov & Vlasov 1994). There have been concerns about further pollution being released in future spring thaws (AMAP 1997; Trade and Environment Database 1997). More chronic concerns are from infrastructure leakages, and also operational issues such as noise (e.g. seismic surveys, equipment operations, transport), physical disturbance from constructions (e.g. platforms, pipelines, storage, buildings), and discharges of wastes (e.g. drilling fluids, mud and rock cuttings, heat, air emissions, discharges of dissolved oils/water from wells, discharges from ships and sewage) (AMAP 1998, p. 663).

Aside from the serious accidents noted above, pollution of the marine environment as a result of oil and gas extraction activities in the Arctic has not yet been widespread. The highest hydrocarbon concentrations detected have been near river mouths, with some evidence of estuarine sediment contamination, although effects remain localized, with those in the Russian Arctic possibly higher than those in the North American Arctic (AMAP 1998, p. 679). Levels in the ambient marine environment are low and not expected to have significant ecological impacts, and levels of hydrocarbons in fish tissue are generally low (AMAP 1998). This is in part because the scale of activities to date has been relatively small, although there is concern that as production levels increase, particularly in the continental shelf areas of the Beaufort, Barents and Kara Seas, so too will the risks of a substantial spill (PAME [Working Group on Protection of the Arctic Marine Environment] 1996; AMAP 1997). The probability of one or more spills greater than 1000 barrels over the production period of Arctic reserves is estimated as between 58% and 99% (AMAP 1997). These theoretical calculations do not take into account the special risks of operating in the Arctic (e.g. extreme cold, storms, ice hazards), and there are also increased problems of clean up (e.g. slow degradation in the cold, sea ice trapping and transport). Moreover, many species of Arctic wildlife are likely to be sensitive to hydrocarbon pollution, which can destroy the insulating properties of plumage and fur so necessary in the cold environment. In addition, if a spill occurred at a critical location it could affect a large proportion of a population, as many Arctic species breed in large aggregations (AMAP 1997).

*Radioactivity*

As with heavy metals, there are both natural and human sources of radioactive materials. Human sources include fallout from atmospheric tests of nuclear weapons, accidents and releases from nuclear facilities, loss of nuclear-powered vessels and emissions from stored or dumped radioactive wastes (AMAP 1998; Crane *et al.* 2000). Of these, atmospheric testing of nuclear weapons, banned since 1980, has been the largest source of global radioactive contamination. The only atmospheric testing in the Arctic was at Novaya Zemlya, between the Barents and Kara seas, and this was discontinued in 1962. Underground tests were also performed there, and also at Amchitka Island (Aleutian Islands, Alaska; AMAP 1998). The former Soviet Union carried out 17 underground nuclear explosions during 1971–1988 for excavations and mining applications, three of which were near the Arctic Circle and which resulted in significant local contamination (AMAP 1998, p. 564). Underwater tests in 1955–1957 in a fjord on the south-western coast of Novaya Zemlya have contaminated sediments with various isotopes, particularly of caesium and plutonium (Smith *et al.* 1995). Exposure to marine biota is unknown. It was estimated that approximately 750 additional cases of fatal human cancer occurred in Arctic peoples due to nuclear bomb fallout, with people primarily dependent on

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marine ecosystems (e.g. fish, seals) being less exposed to risk than those living on terrestrial food sources such as reindeer (AMAP 1997, 1998).

Nuclear fuel reprocessing plants in the United Kingdom and France have released radionuclides into the marine environment, which have been transported to the Arctic by currents (AMAP 1998; Crane *et al.* 2000). The most significant of these have been from Sellafield, on the north-western coast of England, principally in the mid-to-late 1970s, and mainly in the form of caesium-137 (Kershaw & Baxter 1995; Gray *et al.*1995). Those most exposed were consumers of marine resources close to Sellafield, for whom doses were below recommended maxima, and doses in the Arctic are expected to have been much lower. The increased exposure attributable to all European reprocessing plants in total has been equated to approximately one or two additional cancer fatalities in Arctic peoples (AMAP 1997, p. 114)

Several nuclear power plants operate in the Russian Arctic, on the Kola Peninsula in the west and in the Chukchi region in the east, and several in Scandinavian countries are within 1000 km of the Arctic. These plants make routine releases of radioactive material, although within limits set by international standards (AMAP 1998). The accident at the Chernobyl nuclear power plant in April 1986 released large quantities of iodine-131, caesium-137, caesium-134, strontium-90 and plutonium nuclides, most of which were deposited in the immediate vicinity. However, some were transported to the Arctic by winds, principally to the central Scandinavian region and the western Russian Arctic (AMAP 1998, p. 579). The Arctic marine environment was exposed to relatively low levels of contamination from the accident.

The former Soviet Union dumped radioactive wastes in Arctic seas over the period 1959–91, including for example old reactors, shielding, and other solid and liquid wastes (AMAP 1998). The solid wastes were mostly dumped in fjords at Novaya Zemlaya, while the liquids were discharged into the Kara and Barents Seas (AMAP 1998, p. 591). However, levels of radionuclides in the Kara Sea are low (Povinec *et al.* 2000) and, away from the immediate locality of dumped materials, doses to marine organisms are expected to be low (AMAP 1998; Crane *et al.* 2000).

Substantial quantities of radioactive wastes have been released into rivers from reprocessing plants and as a result of accidents within Russian river catchments that lead into the Kara Sea region of the Arctic Ocean (e.g. the Ob and Yenisey; AMAP 1998; Crane *et al.* 2000). Containment dams and storage ponds have been constructed to try to limit release of large quantities of contaminants downstream. Elevated levels of strontium-90 were observed in the 1960–1980 period (Crane *et al.* 2000). Recent data for the Ob estuary show levels of caesium-137 that are similar to the global background (AMAP 1998), although Crane *et al.* (2000) noted that caesium-137 levels are greater than the global background in the Angara, Yenisey and Ob rivers and in the Kara and Barents Seas. Available data suggest that contamination is concentrated around the source facilities, and containment measures have so far managed to limit the escape of contaminants (AMAP 1997).

The former Soviet Union used nuclear explosives for construction and mining in the Arctic between 1967 and 1988 (AMAP 1998, p. 564). The devices resulted in significant local contamination at three sites, and it is likely that radioactivity leaked into aquatic systems. In 1968, a B-52 aeroplane crashed on sea ice in Bylot Sound, near Thule, Greenland, resulting in an explosion that fragmented nuclear weapons on board. While the USA cleaned up the site, studies later indicated that approximately half a kilogram of plutonium was lost into the sea (Smith *et al.*1995; AMAP 1998, p. 577). In 1978, a Soviet nuclear-powered satellite burned up on re-entry, spreading radioactive debris over a 1000 km path in northern Canada. Russia and a range of other countries operate a number of nuclear-powered civilian and military ships and submarine vessels in the Arctic. There are concerns about disposal of wastes from vessels taken out of service, and some vessels have been lost (for example the Russian nuclear submarines *Komsomolets* in April 1989, and the *Kursk* in August 2000, both lost in the Barents Sea). Radioactive releases from the *Komsomolets* are presently minor, and are not expected to pose a serious risk to marine ecosystems in the future (AMAP 1998). The *Kursk* has now been recovered. There are approximately 150 nuclear reactors in the Russian northern fleet, although data on contaminant releases are largely unavailable.

While the above suggests that radioactive substances might be widespread, in the Arctic Ocean contamination levels are generally low (AMAP 1998; Crane *et al.* 2000; Macdonald *et al.* 2000; Povinec *et al.* 2000) and, because of the effects of dilution and of salts on uptake, fish, seals and whales remain relatively unaffected. Moreover, levels of radioactivity from human sources have been consistently declining since the ban on atmospheric weapons tests, despite some peaks associated with specific accidents or releases.

*Climate change*

The polar regions play a critical role in the regulation of global climate, and changes resulting from increased concentrations of greenhouse gases are expected to manifest themselves in the marine ecosystems in both hemispheres. However, while climatic shifts are generally expected to be more pronounced in the polar regions (IPCC [Intergovernmental Panel on Climate Change] 2001), the exact patterns of change and feedbacks are complex and remain poorly understood. It is expected that the Arctic region will be the first to experience the most substantial changes, with a rise in average surface air temperatures of 4–5°C by the middle of this century (Stouffer *et al.* 1989; Manabe *et al.* 1991). Early indications of such changes have been observed, with increases in average temperatures in spring and early summer (Martin *et al.* 1997), and a recent thinning and decrease in spatial extent of Arctic sea ice (Maslanik *et al.* 1996; Parkinson *et al.* 1999; Wadhams & Davis 2000), as well as a shortening in the sea ice season

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(Parkinson 2000). The rate of sea ice reduction has been reported as almost 3% per decade over the period 1978–1996 (Parkinson *et al.* 1999), with the most frequent below-average summers being in the 1990s (Maslanik *et al.* 1996). Over the last century, average sea ice extents declined by 15% in summer and 8% in spring, with only a slight downward trend in autumn and winter since about 1970 (IPCC 2001, p. 125). The spatial patterns are non-uniform, and so far the greatest reductions have been observed in the Arctic Ocean north of Siberia (60°E–180°E; Serreze *et al.* 1995; Parkinson *et al.* 1999). Moreover, there is some evidence that the rate of reduction has been accelerating in recent years (Johannessen *et al.* 1995). Reductions in sea ice cover are expected to alter air–ocean interactions, surface albedo and salinity gradients, which influence heat transfer, stability of the water column and, in turn, ocean circulation patterns. These types of environmental changes in the Arctic Ocean have already been observed, with significant shifts in regional seawater temperatures and salinity patterns, although the extent to which these changes are part of natural cycles in the Arctic Oscillation or spring from more long-term human modifications of climate is not yet clear (Morison *et al.* 2000).

Changes in sea ice cover have important implications for Arctic marine biota (Tynan & deMaster 1997). All levels of the food web are likely to be affected, ranging from primary production to higher mammals. Sea ice plays an important role in the production of algae, particularly at the ice edge, which in turn supplies nutrients to organisms such as copepods. Copepods and amphipods form a large part of the diet of Arctic cod (*Boreogadus saida*), which is a key species in the regional food chain and one on which many species of seal, and beluga whales (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*) rely heavily as a food source (Tynan & deMaster 1997). In turn, predators such as polar bears (*Ursus maritimus*) depend on seals, and sea ice is also required as a solid substrate on which both seals pup and bears hunt. This highly productive marginal ice zone is therefore of vital importance to the integrity of the Arctic marine food web.

Many species, such as Arctic cod and marine mammals, are closely tied into a sea ice ecosystem (Tynan & deMaster 1997), and fish, particularly cod (*Gadus morhua*), are highly dependent on oceanographic variables such as temperature (Ogilvie & Jónsdóttir 2000). Variations in sea ice cover have been associated with shifts in breeding performance of seals. For example, severe ice years in the eastern Beaufort Sea, particularly along the coast, have been linked to declines in ringed (*Phoca hipsida*) and bearded (*Erignathus barbatus*) seals (Stirling *et al.* 1977). Precipitation changes associated with a warming climate may increase freshwater input to the Arctic Ocean, and in some coastal areas at least this may increase ice cover and impair the breeding performance of some species. The International Whaling Commission has identified the Eastern Arctic bowhead whale (*Balaena mysticetus*), Okhotsk Sea bowhead whale (*B. mysticetus*), beluga whales and narwhals as Arctic cetacean species that are particularly at risk from climate-induced changes, which may be acting in synergy with other environmental forcing factors (Tynan & deMaster 1997).

*Atmospheric ozone depletion*

Substantial losses of atmospheric ozone were first observed over the Antarctic (Farman *et al.* 1985), although it is now confirmed that ozone depletion is also occurring in the Arctic; ozone depletion is a global phenomenon (Pyle 2000). Meteorological conditions conducive to ozone loss are not as severe in the Arctic, so losses are less than in Antarctica and are more variable. Nevertheless, substantial Arctic losses have been reported, and losses are expected to continue well into this century in both polar regions (Pyle 2000). Indeed, because of denitrification processes and properties of the northern polar vortex, ozone losses in the Arctic may actually increase in the next several decades, despite global reductions in atmospheric halogen loading as a result of the Montreal Protocol and its amendments (Pyle 2000). Moreover, increases in greenhouse gases (for example $CO_2$ and $CH_4$) may exacerbate stratospheric cooling, which is more conducive to ozone depletion, and thereby extend the period of expected recovery (Shindell *et al.* 1998).

Ozone depletion increases surface-incident ultraviolet (UV) radiation, particularly the short-wavelength UV-B (280–320 nm) (Neale & Kieber 2000). Marine organisms including bacteria, viruses, phytoplankton, zooplankton and many invertebrate larvae, are sensitive to UV exposure. A theoretical 10–15% reduction in photosynthesis might occur in surface waters under severe ozone depletion (>50%) (Neale & Keiber 2000). Gibson *et al.* (2000) have argued that the variations in the loading of chromophoric dissolved organic matter (CDOM) in the water column, which strongly attenuates UV-B, is likely to be the most important influence in the Arctic Ocean. CDOM is relatively high in the Arctic Ocean, at least in coastal areas, which are strongly influenced by riverine input. Changes in marine CDOM, for example through changes in catchment precipitation, land-use practices, or shifts in ocean circulation or other climate-related effects, can cause much greater variations in the levels of exposure of marine organisms to harmful UV than changes through expected ozone depletion (Gibson *et al.* 2000). Coastal areas may be particularly susceptible to CDOM increases, but areas of the open ocean far from the coast with relatively low levels of CDOM may start to become exposed as the perennial cover of sea ice diminishes.

*Harvesting of marine living 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. For example, fishing accounts for 70% of national income in Iceland (UNEP [United Nations Environment Programme] 1999), marine resources are a staple for many Arctic indigenous communities, and the Arctic is one of the world's most important fishing grounds (PAME 1996). In the past, many Arctic marine mammals were overexploited (Pagnan 2000),

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and many are still considered globally endangered (e.g. bowhead [*Balaena mysticetus*], sei [*Balaenoptera borealis*], blue [*B. musculus*], fin [*B. physalus*] and northern right [*Eubalaena glacialis*] whales, and grey seal [*Halichoerus grypus*] 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 (e.g. humpback whale [*Megaptera novaeangliae*], sperm whale [*Physeter catodon*], beluga whale [*Delphinapterus leucas*], harbour porpoise [*Phocoena phocoena*], and northern fur seal [*Callorhinus ursinus*]; CAFF 2001). Many of these species, and others, appear to be in decline in certain Arctic localities, although in other places 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. Overharvesting has previously led to the collapse of herring (*Clupea harengus*), cod (*Gadus* sp.), whitefish (*Coregonus* sp.) and capelin (*Mallotus villosus*) stocks in some parts of the Arctic (UNEP 1999; Huntington 2000; Pagnan 2000; Northeast Fisheries Science Center 2002). While there is evidence of some recovery (UNEP 1999; OSPAR Commission 2000), not all stocks have recovered (Pagnan 2000) and harvesting pressure remains high in some areas (Northeast Fisheries Science Center 2002). The state of fish stocks in the Arctic is variable, ranging from poor overall in the North-west Atlantic, through to good in Iceland and East Greenland, while in the Barents Sea the status varies by species (Jentoft 2000). The stock of many fish species found in the Arctic appear to be in decline, such as Atlantic cod (*Gadus morhua*), capelin, wolffishes (*Anarhichas* spp.), Greenland halibut (*Reinhardtius hippoglossoides)*, deepwater redfish (*Sebastes mentella*), and possibly Arctic cod (*Boreogadus saida*), although stock trends for particular species vary across the region (CAFF 2001). Again, lack of data makes reliable assessment of the status and trends for some species difficult. It has been noted that the effects of fishing pressure on stock size and stock interactions may coincide with climatically driven variability (OSPAR Commission 2000). There is a high level of natural variability in Arctic fish stocks, suggesting that catch levels should be set more conservatively than has often previously been the case.

## POTENTIAL STATE OF THE ARCTIC MARINE ECOSYSTEM IN 2025

Projections of changes to the Arctic marine ecosystem can be considered according to those attributable to the global forcing factors and those more local in nature. The changes of most profound significance to the Arctic marine ecosystem over the next 25 years are likely to be those associated with human modification of the global climate system. Such changes are expected to be most pronounced in the Arctic because of the nature and dynamics of the environment, to be pan-Arctic and probably to affect all levels in the ecosystem. Local threats, such as from pollution, are by no means to be ignored, but it is unlikely that such problems will extend their reach to alter profoundly the entire marine ecosystem in the manner that might be anticipated from climate change. However, there is also concern that local pressures will add to those of global origin and act synergistically, creating cumulative impacts in particular areas.

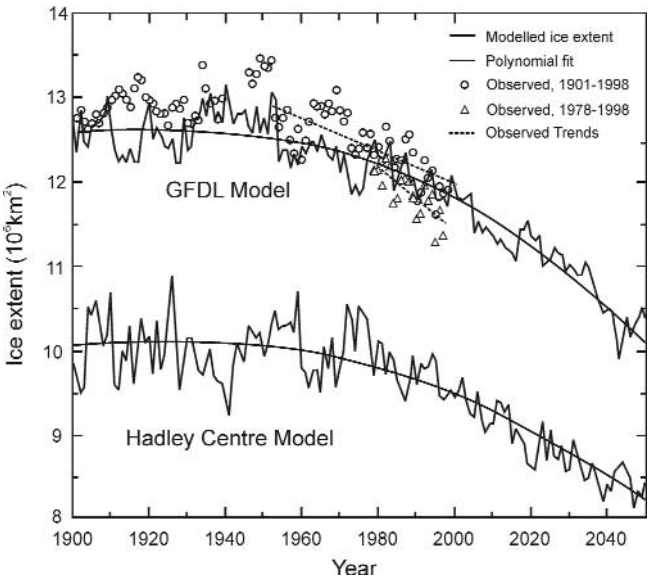



**Figure 6** Observed and modelled variations of annual averages of Northern Hemisphere sea ice extent (from IPCC 2001, p. 447).

The seasonal advance and retreat of sea ice is a key physical process in the Arctic marine ecosystem. Sea ice has important influences on the physical oceanography, including vertical mixing and currents, and changes in patterns of sea ice formation can be expected to result in corresponding changes in the oceanographic system. Sea ice also plays an important ecological role, particularly in the marginal ice zone, which is highly productive and a habitat for a wide variety of marine organisms. There is evidence of both a thinning of Arctic sea ice and of substantial reduction in its spatial extent (Parkinson *et al.* 1999; Wadhams & Davis 2000), and the rate of reduction may be increasing (Fig. 6; IPCC 2001, p. 447). The Hadley Centre and GFDL (Geophysical Fluid Dynamics Laboratory, USA) climate models predict a loss of approximately 10% of Arctic sea ice in the period 1978–2025. However, if the approximately 3% per decade reductions in observed extent data for 1978–1998 (Parkinson *et al.* 1999, updated in IPCC 2001) are extrapolated, even if no allowance is made for accelerating reduction as both the models and observed data suggest, there could be a loss of about 14% by 2025. There are weaknesses in the models, with much yet to be understood about complex feedbacks, and reductions could be greater or less severe. A reduction of 10–14% may not seem catastrophic, although the significance of impact on marine ecosystems will depend as much on where, and when in the season, reductions take place. Other components of the system are also expected to

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experience substantial shifts over this time horizon, such as increases in average surface air temperatures of at least several degrees, as well as rising sea temperatures (IPCC 2001). Precipitation increases have occurred over the last 100 years and are predicted to continue in the Arctic region to 2025 (AMAP 1998; IPCC 2001), which can be expected to affect river discharges and consequently coastal salinity and ecology.

All of these changes are likely to have important implications for the Arctic marine ecosystem, although there is as yet no good understanding of how species numbers and distributions will change, nor how shifting patterns will affect the maintenance of ecological relationships. There is considerable natural variability in the Arctic ocean-climate system, and the large-scale oceanographic changes expected are themselves not well enough understood. Climate models remain too coarse to predict fine-resolution habitat changes, which can have an important influence on the ecosystem response. There is a lack of detailed monitoring data for numerous species, and there are complications in separating climate-related effects from other pressures on the ecosystem. Substantial changes in sea ice and ocean temperature would almost certainly have consequential impacts on species distributions. However, it remains unclear whether changes will automatically lead to declines in productivity, or simply distributional shifts, and the likely magnitude and patterns of such postulated changes are largely unknown.

In addition, the Northern Sea Route (Russian Arctic) and the Northwest Passage (Canadian Arctic) are predicted to open to ship traffic as a result of sea ice reductions brought on by regional warming. There is concern that the anticipated increase in activity will bring with it additional pressures on the marine ecosystem from wastes, noise, spills and accidents, as well as opening up areas for resource extraction (like fishing) and industrial development (Tynan & deMaster 1997).

Despite global reductions in the release of ozone-depleting substances, springtime losses of ozone over the Arctic are projected to increase over the next few decades, in part because more conducive conditions are expected as the northern polar vortex changes in response to expected climatic shifts (Pyle 2000). Bright, reflective snow and ice are likely to intensify the effects of increased UV-B at the surface, although the nature and magnitude of the impacts are largely unknown. Damaging radiation may depress levels of primary production, although relatively high levels of CDOM in the Arctic Ocean are likely to protect against this (Gibson *et al*. 2000). Moreover, organisms may be protected against exposure by pigments, and more resilient species could be favoured, rather than productivity declines being inevitable. On the other hand, Arctic marine planktonic organisms and larvae tend to reside in the upper levels of the water column and are therefore potentially at higher levels of risk to UV exposure (AMAP 1998, p. 754). Changes in CDOM are likely to have a much greater influence on levels of exposure than ozone depletion, and are likely to arise, for example, from water diversions and changes in precipitation, ocean circulation and surrounding land uses (Gibson *et al*. 2000). Higher trophic levels in the food chain could suffer secondary effects from reductions in primary productivity, and could also be affected directly by higher levels of damaging radiation. While the impact on marine ecosystems is not expected to be large, this issue should be kept under review.

It is difficult to single out one of the local environmental threats in the Arctic as being paramount, as all pose issues of concern. It seems likely that levels of heavy metals and POPs in the Arctic environment will present less of a concern in 2025, since, with the exception of mercury, the trend is generally toward a reduction in levels of these elements and compounds (AMAP 1998). However, loadings are unevenly distributed, and reductions are still expected to take at least several decades, and much is still not understood about the means by which elements and compounds enter and move within the Arctic environment (Macdonald *et al.* 2000). Increased industrialization in Asia may reverse the trends toward reduction in some pollutants if emissions controls prove inadequate.

The oil and gas industry may present increasing local risks in the future. First, there are strong indications of substantial hydrocarbon reserves in the Arctic region, which until now have either been too inaccessible or expensive to develop on a large scale. The Arctic climate is expected to ameliorate over the 2025 time horizon, with warming relatively greater than expected elsewhere in the world (IPCC 2001). Key waterways, including the Northern Sea Route (Russia) and the Northwest Passage (Canada, Alaska), are expected to become ice-free for a significant part of the year, making access and exploitation of hydrocarbon reserves easier. Supplies in many other parts of the world are likely to come under increasing pressure, while technologies for exploitation in cold environments are likely to improve. The Arctic marine ecosystem has already been subjected to some of the worst oil spills on record, and the probability of further substantial spills occurring by 2025, even at present levels of activity, is high (AMAP 1997).

Sources of radioactivity are likely to be of increasing concern in the Arctic, especially in the vicinity of northern and north-western Russia. There are concerns about the safety of nuclear facilities in the Arctic and its surrounding region, including power stations, reprocessing plants, storage and weapons facilities, nuclear weapons themselves, and nuclear powered and armed vessels. As these facilities and equipment continue to age and deteriorate, there are increasing risks to aquatic ecosystems generally from releases.

Marine living resources in the Arctic are likely to come under increasing pressures in various ways. Aside from likely direct pressures arising from pollution and climatic shifts, the projected reductions in sea ice may enable freer movement by commercial fishing fleets, expanding areas of potential exploitation. Many existing Arctic fishing grounds are already under severe pressure. With swelling world, and

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perhaps Arctic, human numbers over the 2025 time horizon, demand for marine living resources is likely to increase, and pressures on Arctic fish stocks is likely to grow. For particular commercially valuable species, past experience has shown that conventional approaches to fisheries management have often been unsustainable.

## THE ANTARCTIC MARINE SYSTEM

The Southern Ocean is bounded to the north by the Polar Frontal Zone (between the Antarctic Polar Front, previously known as the Antarctic Convergence, and the Subantarctic Front) and to the south by the Antarctic continent. It comprises 9.6% of the world's oceans, and is predominantly very deep (3000–4000 m). There is a very small resident human population (up to 6000 at summer peak, mostly science and support staff), and a developing tourism industry. This has grown rapidly over the last 10–15 years, with between 10 000 and 15 000 visitors per year recently, mostly on cruise ships to the Antarctic Peninsula during the period November–March (data from the International Association of Antarctic Tour Operators, URL http://www.iaato.org).

The Antarctic continental shelf is unusually deep (typically 700–800 m, and >1200 m in some places). This great depth results from isostatic depression caused by the massive ice cap, and scouring of the shelf by periodic extensions of the ice sheet. Although in some areas the continental shelves are narrow and in many places are overlain extensively by ice shelves, their average width of 125 km is almost twice that typical of continental shelves elsewhere. This large average is caused predominantly by the vast embayments of the Ross and Weddell Seas (Clarke & Johnston 2003). In contrast to continental shelves elsewhere, there are no major rivers discharging into the Southern Ocean. Sediment transport is exclusively by ice, and freshwater input solely from melt or precipitation. This forms a strong contrast with the Arctic.

The predominant surface water circulation is circumpolar and in a westerly (clockwise) direction, driven by the prevailing winds. This Antarctic Circumpolar Current (ACC) is the strongest surface current of any ocean, and combined with the Polar Front forms a very effective biogeographic barrier to all but the most mobile marine organisms such as birds and marine mammals, which migrate across the Antarctic Polar Front to and from breeding or feeding grounds (see Croxall & Wood 2002). Below the cold surface waters are warmer layers (circumpolar deep water), which may on occasion penetrate onto the continental shelf. In certain areas, especially in the Weddell Sea, very cold Antarctic bottom water is formed. This flows northwards, and influences the benthic environments of all oceans (Orsi *et al*. 2001). Although the surface circulation of the Southern Ocean is dominated by the ACC, close to the continent circulation is more complex. An easterly coastal current dominates over many areas of continental shelf, and in areas such as west of the Antarctic Peninsula the oceanography can be complex (Smith *et al*. 1999). Particularly important is the role of upper circumpolar deep water, which is derived from the ACC, and which appears to exert a significant influence over the pelagic marine ecosystem (Prezelin *et al*. 2000).

The surface area of the Southern Ocean is just below 35 million km$^2$. Of this up to 21 million km$^2$ is covered by ice at the winter maximum, but only about 7 million km$^2$ surface ice remains at the summer minimum (Gloersen *et al*. 1992). Two influential schemes for subdividing this vast area into biologically meaningful zones are those of Tréguer and Jacques (1992), based predominantly on ice and nutrient dynamics, and Longhurst (1998), based on upper water column structure and remotely-sensed phytoplankton pigments.

The dominant environmental factors in the Southern Ocean pelagic ecosystem are the seasonality in light and in surface sea ice, which in contrast to the Arctic basin is predominantly annual. Primary production in Antarctica is moderately high, and intensely seasonal. Standing crops of chlorophyll are highest over the continental shelf or close to the marginal ice zone, and can reach very high levels (>40 μg l$^{-1}$). The dominant herbivores are copepods, salps and euphausiids, with Antarctic krill (*Euphausia superba*) playing a central role in the marine ecosystem. Squid and some fish are important consumers, and there are large populations of top predators, including penguins, albatrosses, petrels and marine mammals.

The benthic fauna of the Southern Ocean is generally rich and diverse although bivalves, decapods and teleost fish are markedly low in diversity. Other taxa are notably diverse, including pycnogonids, echinoderms and several suspension-feeding groups (Clarke & Johnston 2003). There are also striking radiations in two groups of fish, notothenioids on the continental shelf and liparids in deeper water (Eastman & Clarke 1998). The predominant biogeographical patterns are circumpolar, with the Subantarctic islands forming distinct regions and a suggestion of a division in high Antarctic (continental) and Antarctic Peninsula regions (Dell 1972).

The proposed biogeochemical divisions of the Southern Ocean pelagic system and the biogeographical zonation of the benthos are quite different schemes. Surface processes are, however, relevant to the benthos in that almost all life on the seabed depends on the flux of material from surface waters for its energy and nutrients. On a very broad scale, patterns of surface production will therefore influence the diversity, abundance and ecology of benthic organisms, albeit modified by advective processes (Clarke & Johnston 2003).

### Environmental forcing factors in the Southern Ocean

A perennial difficulty for scientists attempting to detect anthropogenic change is to do so against a background of natural variability in the system. The Southern Ocean is subject to marked variability on a variety of scales, the most important of which in the present context are seasonal and sub-decadal (although there is also important variability on

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longer time-scales; Leventer *et al.* 1996). As is typical of high latitudes, the Southern Ocean marine ecosystem is intensely seasonal, with most biological activity constrained to summer. There is, however, also significant year-to-year variation.

A major problem in determining the scale and pattern of interannual variability in the Southern Ocean system is that there are so few data sets of sufficient duration to permit robust analyses. Satellite data are available from the early 1970s, but the only longer runs of environmental data for Antarctica are meteorological data from a number of research stations, and a single sea-ice data set from the South Orkney Islands (Murphy *et al.* 1995), both of these extending to the first decade of the 20th century.

The duration of winter fast-ice at the South Orkney Islands shows two key features, a long-term secular change between about 1920 and 1960, and period of marked cyclicity between the early 1960s and the early 1990s (Fig. 7). The satellite record indicates that the fast-ice data reflect ice dynamics over a wider regional area and the cyclicity evident throughout much of the second half of the century is linked intimately to the El Niño Southern Oscillation (ENSO; Murphy *et al.* 1995). The period of this cyclicity is 7–8 years, and reflects the propagation of sea-ice anomalies around Antarctica (Murphy *et al.* 1995). This circumpolar precession has been shown to involve the coupled ocean/ice/atmosphere system and has become known as the Antarctic Circumpolar Wave (White & Peterson 1996).

The Antarctic Circumpolar Wave emphasizes the importance of the ACC in propagating climatic variability, particularly that related to ENSO, around Antarctica. The ACC is also important in advecting biological material, as is particularly well illustrated by the links between the pelagic system off the western Antarctic Peninsula and the system at South Georgia. A particularly striking manifestation of this linkage is in the year-class strength of adult *Euphausia superba* transported by the ACC from their breeding grounds off the west coast of the Antarctic Peninsula to South Georgia. The ACC has been shown to be the primary mechanism for transporting *Euphausia superba* to South Georgia (Hofmann *et al.* 1998); variability in reproductive success of krill off the west Antarctic Peninsula will thus be manifest as variability in year-class strength at South Georgia, modified by survival and growth processes during transport across the Scotia Sea (Fach *et al.* 2002). This variability in the population dynamics of *Euphausia superba* thus generates significant variability in the South Georgia ecosystem (Murphy *et al.* 1998; Atkinson *et al.* 2001; Murphy & Reid 2002), where it has a major influence on the reproductive success of krill-dependent predators (Croxall *et al.* 1999; Reid & Croxall 2001). Data for gentoo penguin, *Pygoscelis papua*, at South Georgia are shown in Figure 8. The critical feature of the poor breeding performance years shown in Figure 8 is their frequency: the population may be able to withstand occasional bad years, but not frequent ones. An important aspect of sub-decadal change is thus whether the frequency of ENSO-mediated events is increasing, possibly as a consequence of secular climate change (Fig. 7).

All of the environmental forcing factors derived from the global sources of pollution noted in the Arctic have been detected in the Antarctic (Table 2), although at much lower levels (Wolff 1992, 1994). Global sources are dominated by those originating in the southern hemisphere, but local sources of pollution pressure are in several cases quite different from those in the Arctic. For example, all mineral

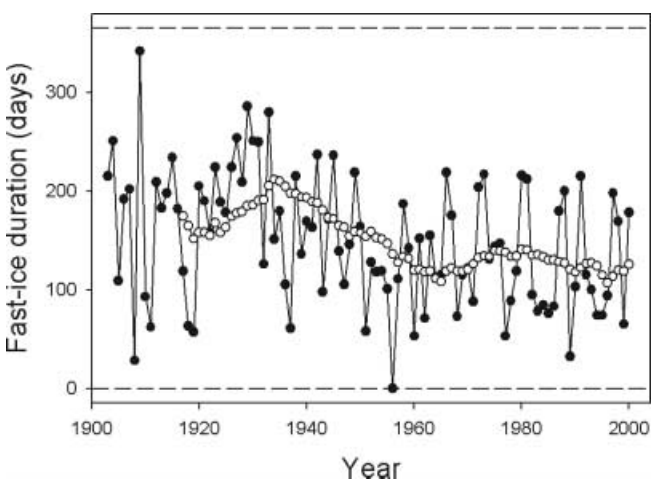



**Figure 7** Duration of winter fast-ice at South Orkney Islands. Data for individual years are shown in black; the clear circles show a tapered 15-year running mean (redrawn from Murphy *et al.* 1995). Data to 1994 were collated from visual observations; data from 1995 were taken by an automatic camera taking four images every day throughout winter.

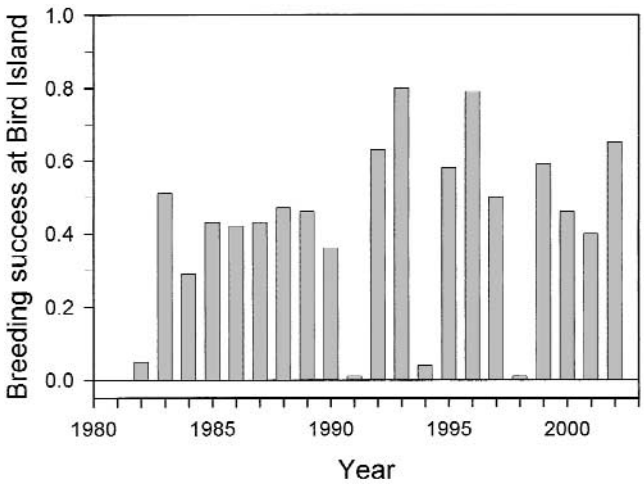



**Figure 8** Variation in the reproductive success of Gentoo Penguin, *Pygoscelis papua*, at South Georgia, showing the poor breeding performance in years of low availability of Antarctic krill, *Euphausia superba* (1982, 1991, 1994 and 1998). Unpublished BAS data (K. Reid, personal communication 2002).

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**Table 2** Principal environmental forcing factors and impacts on the Antarctic marine ecosystem.

| *Key sources* | *Environmental forcing factors* | *Magnitude of pressures and principal impacts* |
|---|---|---|
| Global (industrial pollutants, waste disposal, pesticides, herbicides) and local (waste disposal at research stations) | POPs | Detected, but levels exceptionally low. Some local 'hot spots' at old (discontinued) waste disposal sites at research stations, but impacts confined and very small. Unclear to what extent levels detected in marine birds and mammals originate while animals are outside of the Antarctic region |
| Global (burning fossil fuels) and local (waste disposal at research stations) | Heavy metals | Detected, but levels exceptionally low. Impacts not detected |
| Global (burning fossil fuels, industrial pollutants, ore processing) | Acid rain and sulphur deposition | Detected, but levels exceptionally low. Impacts not detected |
| Local (transport, storage and consumption of fossil fuels) | Fossil fuel use | Oil spills such as *Bahia Paraiso* killed relatively small numbers of seabirds and marine organisms. Impacts localized and transient. Other large marine spills in Antarctic marine environment have not yet occurred |
| Global (atmospheric testing) and local (accident) | Radioactivity | Detected but levels low. Accident at McMurdo Station, Ross Sea, nuclear reactor in 1960s contaminated local soils, which were removed from Antarctica: impact on marine ecosystem unknown but expected to be very low |
| Global (burning fossil fuels, industrial pollutants, forestry and agricultural practices) | Climate change | Some evidence for regional warming, particularly on Antarctic Peninsula, where several ice shelves have disintegrated over last few decades. Changes non-uniform, although expected to be less than Arctic in near-term. Impacts on ecosystem poorly known, although potentially substantial |
| Global (industrial pollutants) | Ozone depletion | High depletion over Antarctic, although expected to have peaked. Improvement expected over next 25 years. Impacts on marine ecosystem not well known, believed to be minor at present |
| Local (marine living resource extraction) | Fishing | Southern Ocean fishery has severely reduced stocks of some fish, and some marine mammals. Recovery of stocks of fish and whales slow; southern fur seal stocks have recovered. Fishing outside Southern Ocean has by-catch impact on some seabirds which breed south of the Polar Front, but which may feed at lower latitudes. Impact particularly severe on albatrosses and larger petrels |
| Local (tourism and science activity) | Physical disturbance | Some concern about repetitive stress to breeding wildlife through physical presence and/or disturbance by scientists and tourists. Impacts on marine organisms unknown although expected to be minor |

resource extraction is banned in Antarctica, and the principal forms of human activity are limited to scientific research, fishing and tourism. Human impacts on the Antarctic marine ecosystem derived from local sources thus stem from these three principal sources. Of these, the pressure of greatest significance in the marine environment at present is fishing (Table 2).

Threats from tourism are currently small. Although there is some concern over excessive disturbance to bird colonies that are visited regularly, these visits are usually well supervised and there is currently little evidence of detrimental effects (Cobley & Shears 1999; Cobley *et al.* 2000). There has been one significant marine pollution event from a support vessel (the sinking of the Argentine vessel *Bahia Paraiso* near Palmer Station, Anvers Island, Antarctic Peninsula, in 1989), but the impact was localized and relatively transient (Kennicutt & Sweet 1992).

Research stations, particularly the older or larger ones, do have impacts (such as sewage outfall, oil spillages and residual material from former dumping of rubbish in the marine environment), although this is generally concentrated in the immediate area of station developments (Harris 2001). Anthropogenic contamination can be detected by sophisticated assays, but the impact of modern research stations on the local marine environment is typically very low (Cripps 1992). Furthermore, new environmental regulations introduced under the Protocol on Environmental Protection to the Antarctic Treaty (ATCPs [Antarctic Treaty Consultative Parties] 1991) for all Antarctic activities means that the impact of scientific research itself is generally scrutinized and regulated. The following discussion of trends in the Antarctic marine ecosystem will focus on those global and local forcing factors that are considered to be of most cause for environmental concern.

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## Environmental trends in the Antarctic marine ecosystem

### *Climate change*

The polar regions are an important part of the global climate system, and can influence the response of the system to the accumulation of greenhouse gases in the atmosphere. Global circulation models are used to predict how the climate of Antarctica may change over the next century, but the details differ from model to model. Most models, however, predict relatively modest temperature increases around Antarctica for the next 50 years and over this period, increased precipitation (snowfall) over the continent should more than compensate for increased melting of Antarctic ice. The problem, however, is that many processes taking place in polar regions are not well represented in these climate models (Connolley & O'Farrell 1998). This is particularly true for the Antarctic Peninsula, where none of the current models predicts either the strong regional warming observed to date, or warming over periods much beyond 50 years into the future (Vaughan *et al.* 2001).

Few Antarctic stations have climate records extending back further than 40 years. This makes it difficult to determine whether the observed temperature changes in Antarctica reflect those in the global record, which shows an overall warming trend of 0.6 ± 0.2°C during the 20th century (IPCC 2001). An extra problem is that temperature records from Antarctica are characterized by a very high level of interannual variability, which makes the determination of trends from short records very problematic. Over much of Antarctica (excluding the Antarctic Peninsula), warming trends have been very small and there has even been minor cooling in recent years at the South Pole (Vaughan *et al.* 2001).

In contrast to continental Antarctica, the central and southern sections of the western coast of the Antarctic Peninsula are showing a marked regional warming. Climate records in this region extend back 50 years and over this period annual mean temperatures have risen by about 2°C (King 1994). Because the current generation of climate models are unable to reproduce this warming (Vaughan *et al.* 2001), any future climate scenarios for Antarctica must be treated with great caution. We do know, however, that the climate of the Antarctic Peninsula area is highly sensitive because of complex interactions between atmosphere, oceans and sea ice, and is strongly influenced by climate variations in the subtropical and tropical Pacific Ocean (King & Harangozo 1998).

The warming has already had a significant impact and is believed to have caused the disintegration of both the Wordie Ice Shelf (Doake & Vaughan 1991) and the northern part of the Larsen Ice Shelf (Vaughan & Doake 1996). Overall, the rapid regional warming of the Antarctic Peninsula has resulted in the loss of seven ice shelves during the past 50 years (Vaughan & Doake 1996). Amongst these is the Prince Gustav Channel ice shelf, which collapsed in 1995. Sediment cores show that prior to its collapse this ice shelf had been present for about 1900 years; before this, for the period 6000–1900 years ago the ice shelf had been absent, and the climate was as warm as it has been recently (Pudsey & Evans 2001).

The regional warming has also resulted in a consistent decline in the extent of small bodies of snow and ice (Fox & Cooper 1998), and populations of terrestrial plants have increased (Fowbert & Lewis Smith 1994; Lewis Smith 2001). There is no evidence of any southward extension of range of the two native vascular plants, probably because there is no suitable habitat at higher latitudes than the current limits to distribution in southern Marguerite Bay. However local populations are expanding rapidly, with spread on scales of metres to kilometres, filling in gaps so that where there were occasional plants there are now larger patches (Convey 2003). The observed rates of regional climate change may also have implications for the lifecycles of terrestrial or freshwater animals (Arnold & Convey 1998), especially as a rapid response to this climate change has recently been reported on freshwater lakes (Quayle *et al.* 2002).

There are very few data for temperature change in the Southern Ocean, and those that do exist are often based on isolated observations or limited comparisons (see Green 1998), which makes detection of a trend against the background of natural variability all but impossible. Global ocean temperatures have shown substantial warming in the upper 1000 m, averaging about 0.1°C between 1955 and 1995 (Levitus *et al.* 2000), but the detection of any warming trend in the Southern Ocean has been severely hampered by the limited number of shipboard observations south of the Polar Front. Gille (2002) has, however, used data from ALACE (autonomous Lagrangian Circulation Explorer) floats to indicate a warming of about 0.17°C between the shipboard vertical temperature profiles taken in the 1950s and those recorded in the 1980s. These data are for depths of 700–1000 m, and suggest that the ACC is warming faster than the global ocean, and at rates comparable with the observed atmospheric warming.

The extent of winter sea ice around Antarctica is believed to be a sensitive indicator of climate change, but it has only been possible to determine the extent of sea ice synoptically since the advent of satellite observations in the early 1970s. Like the temperature record, sea ice distribution is very variable between years. In recent years, a reduction in sea ice extent in some regions (Jacobs & Comiso 1993) has been balanced by an increase in others and there is no evidence for a decline in overall sea ice extent around Antarctica (Zwally *et al.* 2002). The variability of the sea ice record is demonstrated by the record of winter fast-ice duration for the South Orkney Islands (Fig. 7). The lack of primary environmental data for the Southern Ocean increases reliance on proxy records, and De la Mare (1977) has used whaling records to demonstrate a secular change in the mean position of the summer sea ice edge between the mid-1950s and the early 1970s. Although these records come from an area to the east

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of that for which the South Orkney Island fast-ice data can be reliably regarded as representative, and records summer ice extent rather than winter fast-ice duration, the coincidence in the timing of the secular change suggests strongly that something in the Southern Ocean climate system changed significantly during the middle of the 20th century.

*Ozone depletion*

The first report of the Antarctic ozone hole provided an early warning of the thinning of the ozone layer worldwide (Farman *et al.* 1985). Ozone is destroyed in the Antarctic spring by chlorine formed during the sunless winter. This chlorine is derived ultimately from chlorofluorocarbons (CFCs), which have been broken down previously by UV radiation in sunlit regions; the destruction of ozone takes place on the surface of small stratospheric cloud particles, which only form in the intense cold of the polar winter. The amount of ozone in the stratosphere undergoes a regular seasonal pattern, but since the mid-1970s there has been a marked reduction in the amount of ozone over Antarctica during the spring minimum (Fig. 9).

The CFCs and halons that provide the chlorine that destroys ozone are released primarily in the northern hemisphere. This demonstrates graphically the extent to which pollution can affect the entire Earth through global patterns of atmospheric circulation. Concerns over the environmental impact of the thinning of the ozone layer led to the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987 (UNEP Ozone Secretariat 2000). If the provisions of the Montreal Protocol are strengthened and followed, there is a reasonable prospect that the Antarctic ozone hole will recover.

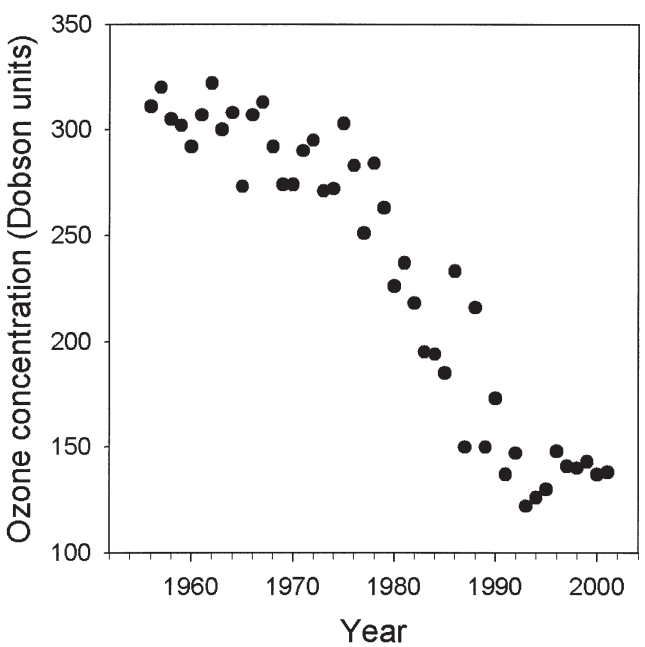



**Figure 9** Total ozone above the British Antarctic Survey station at Halley (British Antarctic Survey data). Data are monthly means for October, the month of minimum ozone levels. Note that the paper first reporting the existence of ozone depletion above Antarctica was published in 1985 (Farman *et al.* 1985).

Most atmospheric ozone is in the lower stratosphere, at an altitude of 20–25 km, where it forms the 'ozone layer'. It acts as a shield by absorbing biologically damaging UV light (specifically UV-B). Some evidence for direct effects from an increase in the UV-B radiation in Antarctic waters has been found by comparing phytoplankton productivity both within and outside the area of the sea beneath the ozone hole, with a 6–12% reduction in phytoplankton productivity indicated in the Antarctic marginal ice zone (Smith *et al.* 1992). However, others have suggested that marine phytoplankton might have protective mechanisms (Karentz *et al.* 1991), and that the displacement of UV-sensitive species by UV-tolerant ones might be more important than a decline in overall productivity (McMinn *et al.* 1994). The ozone hole appears in spring, at a time when many areas are still covered by seasonal ice. At present it is not clear to what extent the spring ozone hole is having, or may have in the future, an impact on the marine system of Antarctica.

*Fishing*

Fishing within the Southern Ocean has a long history. Following the exploratory voyage of Captain James Cook in the 18th century, an active fishery for southern fur seal (*Arctocephalus gazella*) developed rapidly. The first sealers reached Antarctica 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 the original stocks were depleted. By 1822, a period of only 35 years, the southern fur seal was almost wiped out and the industry collapsed (Bonner 1982). The large numbers of great whales found in the Southern Ocean had 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 collapsed economically, although it is now clear that significant unregulated whaling of protected stocks also took place subsequently, and some residual fishing for Minke whales, *Balaenoptera bonaerensis*, continues. In the first half of the 20th 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 (Fig. 10), 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 five years the stocks of *Notothenia rossii* at South Georgia

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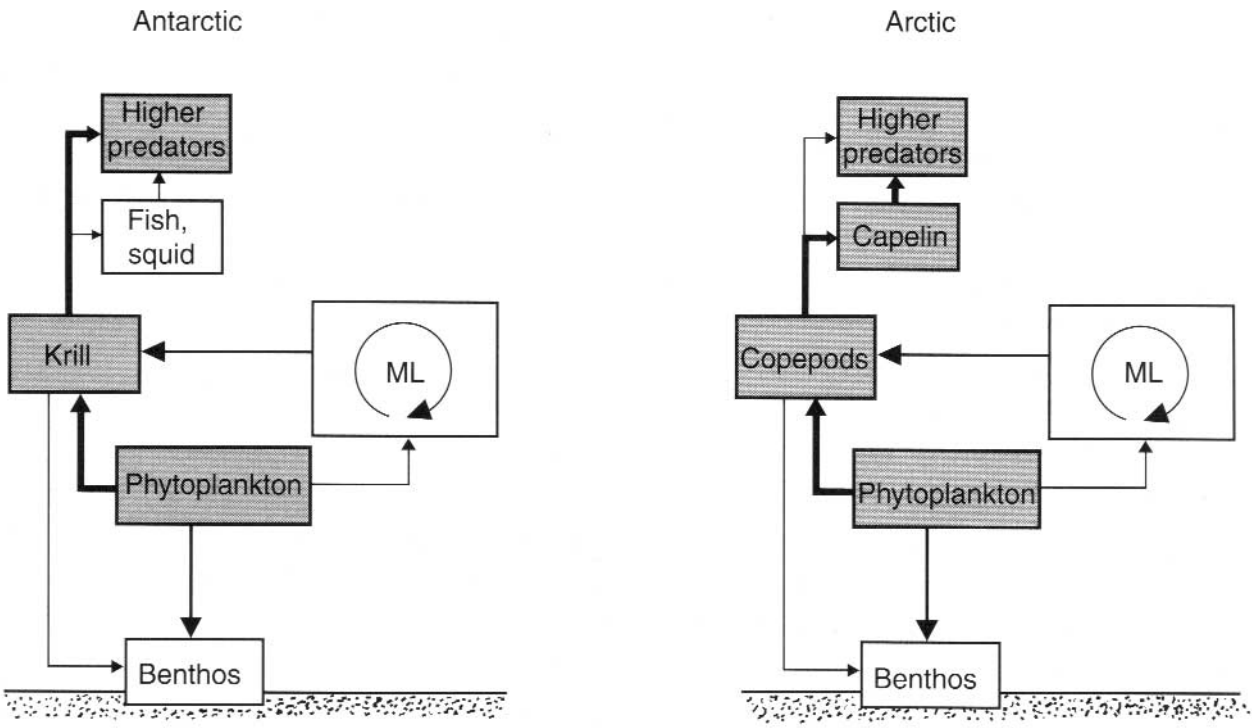



**Figure 10** Two representative polar marine food webs, emphasizing the non-linear nature of the pelagic marine ecosystem. Although Antarctic krill can be important in some places at some times (for example at South Georgia) in others copepods are more important. These differences are shown by the shading in the two food webs. The basic structure of the marine food web is similar in the Arctic, though the species making up the main compartments are different. ML = microbial loop.

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. A trawl fishery for Antarctic krill also developed in the 1970s. 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), itself through fishing activities, might have resulted in a krill surplus. The Southern Ocean food web is, however, complex and non-linear (Fig. 10), and this makes the response of the system to fishing pressure very difficult to predict (see, for example, Fraser *et al.* 1992). It is quite possible, for example, that the response may have been an increase in the populations of other krill predators such as fish, squid or seabirds. In the absence of population data, it is impossible to know whether a krill surplus ever existed. Similar problems surround prediction of responses within the Arctic marine system, which has a similar basic structure, though the components of the various trophic levels differ.

The total catch of krill increased during the late 1970s to a maximum of over 500 000 tonnes in 1982. The current 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 2001). This convention is now responsible for the regulation of all Southern Ocean fisheries, excluding exploitation of whales and seals, which are covered by separate conventions. The CCAMLR area is different to that of the Antarctic Treaty, applying 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 (Fig. 11).

CCAMLR was the first fisheries management regime to take an 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 (Everson 2002). A key mechanism for achieving this is the CCAMLR Ecosystem Monitoring Programme (CEMP),

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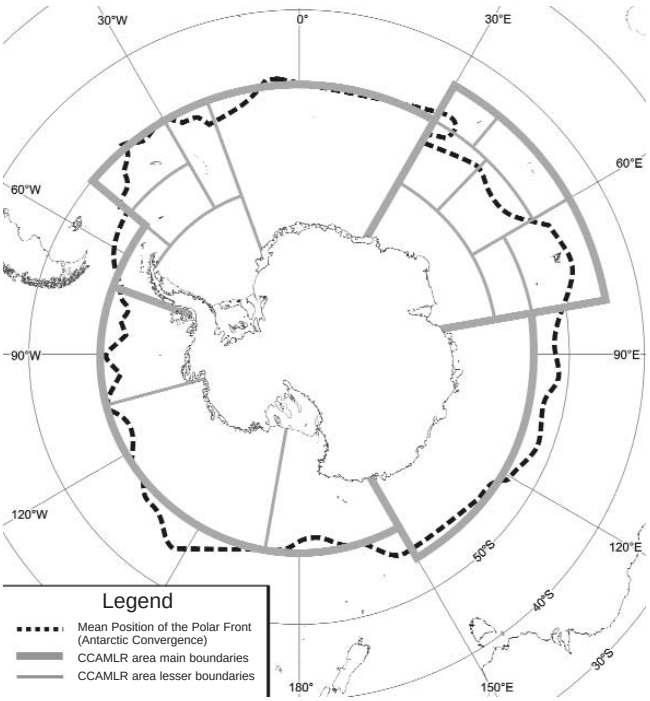



**Figure 11** The CCAMLR area. The thin lines mark different reporting zones for fishery data within the overall CCAMLR area. Note that the boundary of the CCAMLR area is close to the mean position of the Polar Front, and the CCAMLR area thus includes some areas excluded from the area covered by the Antarctic Treaty System (for example South Georgia).

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).

The major fisheries-related threats to the Southern Ocean ecosystem currently come from illegal, unreported and unregulated (IUU) fishing and the impacts on seabirds feeding outside the Southern Ocean. Although the fishery for Patagonian toothfish within the CCAMLR area is regulated, there is 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 Pantagonian toothfish fishery, and for CCAMLR.

The other area of great conservation concern is the mortality of seabirds (albatrosses and larger petrels), which are killed in long-line fisheries outside the Southern Ocean. This mortality is leading to a severe 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 (Agreement on the Conservation of Albatrosses and Petrels 2001) was concluded 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 United Kingdom). With numerous key fishing countries yet to sign up, it is too soon to assess the agreement's practical effect.

## SUMMARY OF ENVIRONMENTAL TRENDS IN THE ANTARCTIC MARINE ECOSYSTEM

It is very difficult to detect any clear trends for the Antarctic marine ecosystem as a whole. There are, however, localized trends in some specific areas. The regional warming evident in the western Antarctic Peninsula is having an impact on sea ice, together with the abundance and distribution of some ice-dependent species. A significant inverse correlation has been demonstrated between air temperature and sea ice extent, including a significant lengthening of the ice-free period during spring and summer (Smith & Stammerjohn 2001). There are no data to indicate whether these changes are having any effects at lower levels in the Antarctic marine food web, but there is clear evidence of an effect on the top predators, particularly the Adélie penguin (*Pygoscelis adelie*). As well as a gradual shift southwards in the distribution of three penguin species in response to regional warming (Fraser *et al.* 1992; Emslie *et al.* 1998), there are more localized effects indicating changes in the relationship between Adélie penguins and their principal prey during the breeding season, Antarctic krill, mediated through interactions between sea ice and hydrography. Croxall *et al.* (2002) provide a summary of changes in Antarctic seabird populations in relation to sea ice.

Generalizing these important results for the western Antarctic Peninsula to the Antarctic marine ecosystem as a whole would be premature. Not only is the regional warming atypical of Antarctica as a whole, but we also have so few data for much of Antarctica that any speculation as to trends would be highly unreliable. Nevertheless, changes in Adélie penguin populations, mediated through sea ice and oceanography, have been reported from the Pacific sector (Wilson *et al.* 2001). Future threats, such as we can assess them at present, are summarized in Table 3.

## POTENTIAL STATE OF THE ANTARCTIC MARINE ECOSYSTEM IN 2025

Any projection of the state of the marine Antarctic marine ecosystem in 2025 is constrained by two factors. The first is the limited amount of data on the present system and current trends, and the second is the inability of the current generation of global models to simulate the polar regions accurately. Although the current models predict a reduction in sea ice extent on current climate warming trends (IPCC 2001), these predictions have very low precision and should be approached with caution. Attention is currently directed at improving the representation of sea ice in these models, and the next generation of such models should enable prediction of trends in polar regions to be made with much improved precision and reliability.

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**Table 3** Future threats to the Antarctic marine ecosystem, ranked by current importance.

| *Threat* | *Comment* |
|---|---|
| 1. Illegal, unreported and unregulated (IUU) fishing activity | The most important current threat to Antarctic marine ecosystem, with strong potential for damage from IUU, or from overexploitation of selected stocks. Current CCAMLR management routines should prevent damage unless IUU becomes excessive |
| 2. Climate change | Potential impact of continuing climate change (regional or global) severe, but difficult to predict at present |
| 3. Pollution | Increasing threat of localized pollution from increased shipping and aircraft activity, with potential for accidents. A key value of Antarctica is its relatively undisturbed condition; smaller pollution events can have greater significance than occurrences of similar magnitude elsewhere in the world |
| 4. Science and associated support activities | Potential for localized impact, but this will be minimized by adherence to the Madrid Protocol. Risk of hydrocarbon spills from station fuel storage and resupply operations remains, although is not considered high. Scientific activities are wide-ranging in type and extent, although are of modest scale and generally carefully regulated |
| 5. Tourism | Unlikely to pose a major threat in foreseeable future as industry presently small. Given coincidence of peak tourist season with seabird breeding, pressure at particular sites may be moderate. Tourist industry experienced rapid growth over last decade, but future growth difficult to predict, although potentially high |
| 6. Mineral exploitation | Potential threat high should mining eventually be permitted, but current moratorium under Madrid Protocol prevents exploitation |

Because the operation of most of the rest of the Antarctic marine ecosystem is tied intimately to the dynamics of sea ice, we are also unable to make sensible predictions of the likely state of the biological components of the system. It seems reasonable to suggest, however, that the level of human impact through fishing has the potential to exceed the impact of global or regional climate change in the region over the next 20–25 years. The state of stocks in 2025 will therefore have more to do with the success of CCAMLR in achieving sustainable exploitation levels, and regulating IUU activities, than the effects of climate. It is also likely that the status of many seabird stocks will be dictated more by conservation measures to limit incidental mortality than it will by climate change.

## CONCLUSIONS: THE TWO POLAR MARINE ECOSYSTEMS IN 2025

Climate change is likely to present the single greatest long-term threat to the two polar marine ecosystems, although over the time horizon under consideration in this paper this is truer for the Arctic than the Antarctic. The most obvious changes to the 2025 time horizon in the Arctic are likely to occur in the thickness and extent of sea ice. For the Antarctic, some current models predict reductions in sea ice extent, but the reliability of such estimates is low. Changes in sea ice are driven by changes in the ocean-atmosphere system, although alterations in sea ice patterns themselves influence the system through feedback processes. Significant shifts in oceanic and atmospheric properties in both the Arctic and Antarctic have already been observed (in air and sea temperatures and ocean salinity), although it has not yet been established unequivocally whether some of these changes are part of natural cycles or a result of human-induced global warming. Available evidence would strongly suggest the latter, at least for the Arctic, although there is still a need for more long-term data. Moreover, the feedback mechanisms themselves, between land, air and sea, are not well enough known, and predictive models require further development.

Sea ice is a critical habitat in polar marine ecosystems and the marginal ice zone, in particular, is highly productive. The availability of food in this zone also makes it important to a wide variety of marine life, and changes in the extent and distribution of sea ice are likely to have significant implications for numerous species, as indicated by changes in the distribution of penguins along the western Antarctic Peninsula. Yet, just as there are considerable uncertainties in the processes and patterns of change, the precise implications for the marine ecosystem are also poorly known. There is general agreement that animal distributions would be likely to shift, although the scale and nature of such changes, and implications for ecological relationships, reproduction and survival are only poorly understood.

More localized pressures on Arctic marine ecosystems are largely arising from pollution by POPs, heavy metals, radioactivity, and petroleum hydrocarbons. While levels of some POPs found in Arctic marine species have been found to be very high in specific areas, the general downward trend for POP levels suggests that this form of pollution will be of decreasing concern over the next several decades. Rapid industrialization and the efficacy of environmental controls in China and other parts of Asia may have a significant influence on whether these trends continue. The same is true of most heavy metals, although levels of mercury are high in some

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seal and whale populations and rising in some Arctic aquatic ecosystems. This is believed to be a result of the mobility of the metal and the relatively favourable conditions for deposition in the Arctic, although further research is required. Although POPs have been recorded in Antarctic birds and marine mammals, many of these are highly migratory and it is unclear to what extent these burdens reflect uptake outside the Southern Ocean. For Antarctic marine invertebrates, pollutant burdens are generally very low, and are likely to remain so unless there is significant exploitation of mineral resources in the region.

Key concerns over radioactivity and hydrocarbons in the Arctic are of sudden, uncontrolled and catastrophic releases. In the case of hydrocarbons, the probability of such an accident occurring before 2025 is high, especially if the oil and gas industry expands in the Arctic as expected. Depending on where and when they occur, spills have potential for substantial impact on Arctic aquatic ecosystems, particularly in view of the often large aggregations of animals and the relatively slow ecosystem recovery times. In the case of sources of radioactivity, the risk of release may be less than that from hydrocarbons, although potential consequences could be far-reaching. There are many potential sources within or close to the Arctic, and deterioration of ageing nuclear infrastructure is a significant cause for concern. There is an urgent need for high-risk facilities within the Arctic to be assessed and international cooperative steps taken to address the risks of further significant contamination events. Commercial exploitation of living resources is another serious pressure on both polar marine ecosystems, and unsustainable harvesting practices have been frequent. The regulatory procedures in the two polar regions are quite different, and the future of the stocks will depend on the ability of the various regulatory bodies to develop and implement sustainable fishery regimes.

Perhaps of greatest concern for the future state of the two polar marine systems must be the potential for cumulative impacts from multiple sources, combining global pressures in the form of climatic and ozone changes with local pressures in the form of pollution and unsustainable exploitation of living resources. The two polar regions differ markedly in this respect, reflecting the isolated nature of the Antarctic in contrast to the Arctic ocean basin with its almost complete boundary of industrialized continental land masses. While species may be able to withstand and adapt to one, or even several of these pressures, the cumulative impact of a number of impacts operating synergistically may be too much to bear. Moreover, should severe impacts occur at a critical point in the food chain, dependent and associated species are likely to follow suit. In this sense, the polar marine ecosystems are particularly vulnerable and exposed to risk.

Actions for environmental conservation of polar marine ecosystems need to take particular account of the elevated risks stemming from the nature of the environment, the ecosystem structure, and the threats that they face. In the multinational context there is a need for high levels of international coordination, effective systems of data collection and monitoring, formulation of standards and regulations and consistency in their application, and greater technology/knowledge transfer between countries.

Arctic peoples have a long history of close association with the environment, and continue to depend highly on it for their livelihoods. Perhaps the moves evident toward greater self-determination by Arctic peoples will help to secure the environmental integrity of this region. In the Antarctic, there is no native population to voice concerns, which must be expressed largely by the scientists, diplomats, tourists, non-governmental organizations and interested members of the public that are knowledgeable about the region. Securing the environmental integrity of the marine environments in the polar regions will not be achieved, however, without cooperation, investment and significant modifications in the current practices of the main contributors to the problems, mainly the lower-latitude, but higher-consumption, nations of the world.

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