A lone Adélie penguin (*Pygoscelis adeliae*) in front of a spectacular iceberg, Antarctica
Photo by Doug Thost

Antarctic
environment

7

Key findings

The ozone hole has largely protected East Antarctica from global warming.

Over the past half-century, western Antarctic surface temperatures have shown general warming trends with significant regional patterns. The Antarctic Peninsula is warming faster than anywhere else on Earth. In East Antarctica, the lower stratosphere has cooled and changed the atmospheric circulation through the loss of stratospheric ozone. A recovery of the ozone hole will reverse these processes and significantly increase the warming trend in East Antarctica.

The East Antarctic Ice Sheet is losing ice at its coastal fringes.

Although the mass of the whole Antarctic ice sheet has remained roughly the same over recent decades, the coastal fringes of the East Antarctic Ice Sheet have lost about 60 billion tonnes of ice each year since 2006. The annual loss is occurring at an increasing rate and may contribute significantly to sea level rise in the future.

Major regional changes are occurring in Antarctic sea ice coverage.

Over the past 30 years, there has been a small increase in the areal extent of sea ice around Antarctica, but with strong regional differences. Most notable are contrasting regional changes in sea ice seasonality (i.e. timing of annual ice advance and retreat and resultant coverage duration) attributed to changing patterns of large-scale atmospheric circulation. In the Western Antarctic Peninsula region, there is mounting evidence that a shortening of the ice season has affected multiple levels of the marine food web, whereas there is a trend towards lengthening of the annual sea ice season in the Western Ross Sea sector. The signal in the East Antarctic sea ice zone is mixed and complex, and is currently under investigation.

The Southern Ocean is getting warmer.

In the region from 35°S to 65°S, the upper Southern Ocean has warmed by 0.2 °C since the 1950s. This rate of warming is faster than elsewhere in the global ocean. Warmer waters enable alien species to extend their range southwards. These immigrating species are less specialised for the cold environment than Antarctic species, and are likely to outcompete, and perhaps replace, the native species. This could have a significant impact particularly on benthic (ocean floor) communities and ecosystem functioning.

Increased acidification of the Southern Ocean can affect the base of Antarctic food webs.

Dissolved carbon dioxide acidifies the ocean and reduces the availability of carbonate ions that calcium carbonate shell-making organisms require for calcification, diminishing the ability of these organisms to form shells. Change in acidity of the ocean is already affecting calcifying organisms—the shells of planktonic organisms known as foraminifera, which are food for many other organisms, are now about one-third lighter compared with pre-industrial times. These types of changes, which affect the base of the food web, can potentially change the dynamics of the Southern Ocean ecosystem significantly.

Antarctic vertebrates are highly specialised to survive in the Antarctic. Whether they can adapt to new conditions due to climate change is currently unknown.

Antarctic vertebrates encompass a variety of flying seabirds and penguins, several seal and whale species, and numerous fish. In the Antarctic Peninsula region, an apparent decrease in the abundance of Antarctic krill has been attributed to the observed reduction in winter sea ice coverage. This in turn has caused a decrease in Adélie and chinstrap penguin populations. Environmental changes cascade through ecosystems. As the rate of environmental change increases, it may exceed the rate at which vertebrates can adapt. Hence, it is likely that some species will not survive the coming decades.

The pressure of human activities on Antarctica and the Southern Ocean is increasing.

The Protocol on Environmental Protection to the Antarctic Treaty commits signatories to comprehensive protection of the Antarctic environment. Australia has ratified the protocol by establishing legislation to enforce procedures for reducing the impacts of Australians visiting Antarctica and has taken practical steps to reduce the impacts of past activities, such as the clean-up of abandoned waste disposal sites. However, the human footprint in the region is gradually increasing. New stations are still built; tourism to the continent continues to grow, particularly to the Antarctic Peninsula near South America; and, with a growing world population, commercial fishing activities are likely to increase. Adequate resources are needed to monitor the intensity and frequency of all human activities.

We dwelt on the fringe of an unspanned continent, where the chill breath of a vast, polar wilderness, quickening to the rushing might of eternal blizzards, surged to the northern seas. ... We had found the Home of the Blizzard.

Douglas Mawson, *The home of the blizzard*, 1930

The terrestrial ecosystems are changing, especially where snow fall is replaced by rain.

Retreating glaciers, particularly in the subantarctic, higher ambient temperatures and precipitation as rain rather than snow make the terrestrial environment more accessible to plant and microbial communities. A warmer climate and increased availability of liquid water enables their populations to expand and non-native species to become established.

The natural heritage of Macquarie Island has suffered under the impact of introduced species, but a large-scale eradication program is under way.

Introduced vertebrates, such as rats, mice and rabbits, have caused a major deterioration of the natural heritage values of Macquarie Island. Overgrazing by these species in particular has increased landslides, many of which have damaged seabird colonies. A large-scale eradication program is currently under way to rid the island of these alien species.

Contents

The Antarctic increasingly will serve as a barometer of change and an indicator of human impact elsewhere in the globe.

Tony Press, *Antarctica and the future*, in *The Antarctic: past, present and future*, Julia Jabour-Green and Marcus Haward eds, 2001

Eroding iceberg, Antarctica
Photo by Doug Thost

1

Introduction

Antarctica is the southernmost continent and, including all islands and ice shelves, covers an area of about 13.8 million square kilometres (km^2). It is nearly twice the size of Australia. The sea ice that surrounds it adds approximately another 19 million km^2 at its maximum extent in September–October,[1] diminishing to 2–3 million km^2 in February.[2] The annual growth and retreat of the Antarctic sea ice is one of nature's most significant large-scale annual changes. Antarctica is Earth's coldest, highest, windiest and driest continent, and its largest cold desert. Only about 44 900 km^2 or 0.4% of the total Antarctic land mass is ice free.[3] Antarctica also has the deepest continental shelf and is surrounded by the largest wind-driven currents, which circulate the Southern Ocean. It is the only continent that has never had a native human population.

1.1 Global importance of Antarctica

Although isolated from other continents, Antarctica is connected to the rest of world through oceanic and atmospheric circulations. Antarctica and the surrounding Southern Ocean are key drivers of Earth's oceanic and atmospheric systems. A critically important feature is that about 90% of Earth's ice (around 25.2 million gigatonnes)[4-5] is found here, and 70% of all available fresh water is locked up in the Antarctic ice sheet—if melted, this would raise sea levels by nearly 60 metres.[6]

Equally important, between the coastline of the Antarctic continent and the Antarctic Polar Frontal Zone (the boundary between subtropical and subantarctic waters) lies the Southern Ocean, which extends over some 38 million km^2 and encompasses about 20% of the world's ocean waters.[7] The Southern Ocean connects the three main ocean basins (Atlantic, Pacific and Indian) and creates a global circulation system that is largely driven by the eastward flowing Antarctic Circumpolar Current—the world's largest current. The current generates an overturning circulation (movement of water masses of different densities caused by variations in salinity and temperature) that transports vast amounts of heat and also takes up a significant amount of carbon dioxide from the atmosphere.[8] Atmospheric pressure, humidity, air temperatures and wind patterns for our entire planet are interconnected and greatly influenced by processes in the Southern Ocean.

As well as playing an important role in influencing weather patterns, the Antarctic environment provides a valuable benchmark for climate change. The Antarctic continental ice holds one of the oldest and most detailed climate records. Moreover, the Antarctic environment and biosphere comprise highly sensitive indicators of present-day environmental change. Predictions made in the 1980s and 1990s about climate change and its effects in the polar regions in the 21st century have largely been confirmed.[9] The major difference between previous predictions and recent observations is that the forecast change appears to be occurring at a faster rate than originally expected; for example, changes in ice sheets and glaciers are accelerating.[10-12] The western Antarctic Peninsula region has been warming two to three times faster than the global average and has become one of the fastest warming regions on Earth.[13] Over this period, 3 of the 12 ice shelves in the peninsula region have retreated significantly and 4 have collapsed, amounting to a loss of about 18% of the floating ice.[14] However, in East Antarctica, which has been shielded from the effects of global warming by the ozone hole,[15] the warming is less than the global average.[16] The regional differences in the responses to climate warming and variability highlight the complexity of the processes currently affecting Earth's environment.

1.2 The natural environment

The Antarctic environment comprises diverse habitats and ecosystems that include ice-covered areas; ice-free vegetated areas; ice-free rocks; saltwater and freshwater lakes and streams; and the intertidal areas, mid-water, deepwater and benthic regions (the benthic zone is the ecological region at the lowest level of an ocean or lake, including the sediment surface and some subsurface layers) of the Southern Ocean. In the terrestrial environment on the continent, species diversity is low compared with mid-latitudinal or tropical ecosystems; however, many species are very abundant. Species that have made the Antarctic continent their home have evolved over very long timescales so that they are now highly specialised and able to survive in the extreme conditions of the southern continent and the frigid ocean surrounding the continent. Only a few species of terrestrial invertebrates occur and flowering plants are limited in their distribution to small areas at the Antarctic Peninsula. There are no flowering plants in East Antarctica, and lower plants such as mosses, lichens and bryophytes live in the few ice-free areas; algae prosper not only in the marine environment but also in snow fields.

The species composition on the subantarctic islands is quite different from that found on or near the continent. The vegetation of Heard Island, for example, covers ice-free areas of the island and includes a variety of vascular plants (12 species), mosses (44 species), lichens (34 species) and liverworts (17 species).[17-18] Macquarie Island supports 45 species of vascular plants and 91 species of moss, as well as a large number of lichens and liverworts.[19]

Land-breeding vertebrates are represented by only a few species. However, they tend to occur in large numbers on both the continent and on the subantarctic islands. The most diverse vertebrate groups comprise flying seabirds (seven species) and penguins (two species on the continent and five on subantarctic islands); four species of ice-breeding seals, fur seals and elephant seals are also part of the Antarctic fauna.

King penguins (*Aptenodytes patagonicus*), Macquarie Island
Photo by Nick Rains

The abundance of terrestrial invertebrates varies regionally and depends upon the conditions of the local microhabitats and particularly the topography and vegetation.[20] Many invertebrates live under rocks or in the relatively moist moss beds, Antarctica's 'forests', where moisture is available.[21] The species diversity is low; the most abundant phyla are rotifers (wheel animals), nematodes (worms) and tardigrades (water bears) but mites and springtails are also found.[20,22] The terrestrial species diversity of the region pales in comparison with the marine species. Invertebrate taxa living at the continental shelf (0–1000 metres) and in the deep ocean (>1000 metres) encompass more than 3500 species.[23] Creatures such as seaspiders, sea urchins, marine worms, molluscs and sponges are highly diverse with a large percentage of endemic species (i.e. species unique to the region).[23-25] The list of species is expected to grow with the publication of a large-scale, international survey of the Southern Ocean—the Census of Antarctic Marine Life of 2007–08.[a] Antarctic fish are also often endemic and are dominated by notothenioids (icefish), which make up more than half of the 320 fish species known to exist in the Southern Ocean.[26]

Marine microbes are highly abundant and constitute most of the biomass in the Southern Ocean; they play a crucial role in the turnover of nutrient cycles.[27-28]

1.3 Antarctic governance

The Antarctic Treaty and a set of related international agreements, known collectively as the Antarctic Treaty System, provide the framework for governance of the Antarctic region.

1.3.1 Antarctic Treaty

The Antarctic Treaty and related instruments of the Antarctic Treaty System provide the international

a www.caml.aq

framework for management of the Antarctic region. From the 12 original signatories (including Australia) in 1959, membership of the treaty has now grown to 48 countries. The Antarctic Treaty area—the area south of 60°S—comprises 10% of our planet's total surface area. Australia is one of seven countries that claim territory in Antarctica. While the Antarctic Treaty is in place, territorial claims are effectively set to one side and the Antarctic is available to be used by any nation for peaceful purposes. Russia and China have maintained stations in the region administered by Australia (Figure 7.1) for many years and India is currently building a station.

Australia was instrumental in the negotiations leading to the treaty and, together with France, instigated the negotiations that resulted in the 1991 Protocol on Environmental Protection to the Antarctic Treaty. The Madrid Protocol, as it is known, establishes an internationally agreed framework for comprehensive protection of the Antarctic environment. It designates Antarctica as a 'natural reserve, devoted to peace and science'. Activities subject to the protocol must undergo an assessment of environmental impacts and then be conducted in a manner that limits adverse impacts on the Antarctic environment and dependent and associated ecosystems. Each signatory state is required to create enabling legislation to give effect to the environmental protection measures of the protocol on the activities of their national programs and citizens while in Antarctica. The Antarctic Treaty does not apply to Australia's subantarctic Islands.

1.3.2 Convention on the Conservation of Antarctic Marine Living Resources

Conservation of Antarctic marine living resources is subject to the regulations imposed under the Convention on the Conservation of Antarctic Marine Living Resources. This convention came into force in 1982 as part of the Antarctic Treaty System. Article 1 of the convention defines its area of operation as 'the area south of 60° South latitude and … the area between that latitude and the Antarctic Convergence which form part of the Antarctic marine ecosystem'.[29] The Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR) was established because of a general concern among the treaty parties that an increase in krill catches in the Southern Ocean could have a serious effect on populations of krill and other marine life; particularly on birds, seals and fish, which mainly depend on krill for food. Antarctic krill (*Euphausia superba*) was first fished in the 1960s at low levels (4 tonnes in 1961–62 and 306 tonnes in 1964–65) as an exploratory fishery.[30] Commercial exploitation began only in the late 1970s and early 1980s when around 500 000 tonnes of Antarctic krill were caught each year.[31] CCAMLR was initiated in response to this rapid expansion of the krill fishery.

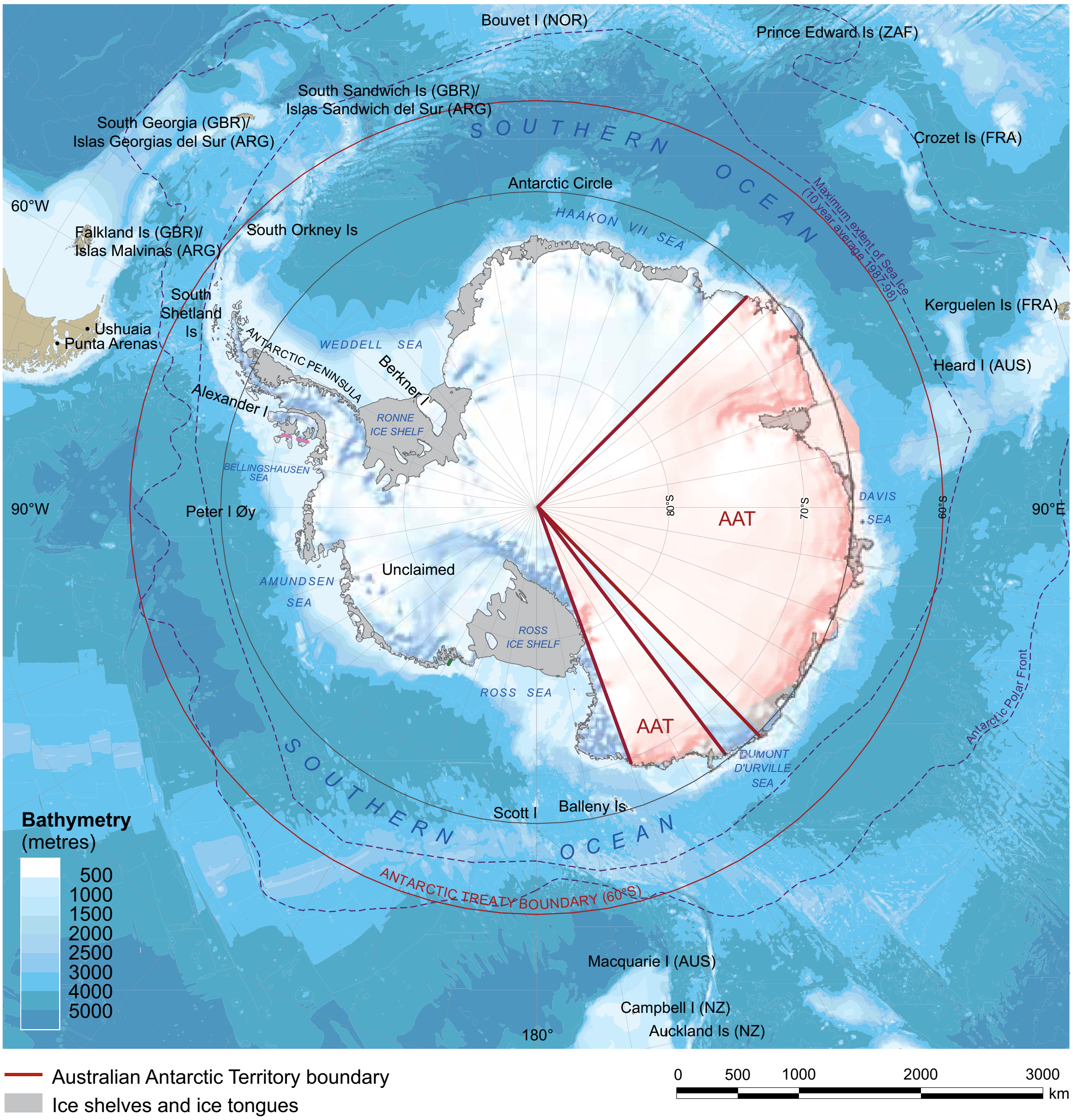
The philosophy underlying this convention aims to ensure not just a sustainable fishery but a sustainable ecosystem. This sets CCAMLR apart from regional fisheries management organisations, which focus solely on the management and production of harvested species. CCAMLR considered the needs of krill-dependent predators and set catch limits to ensure their needs were met. A number of krill-dependent predators were selected as indicators of the health of the Southern Ocean ecosystem and the CCAMLR Ecosystem Monitoring Program was developed. Its aim is 'to detect and record significant changes in critical components of the ecosystem to serve as a basis for the conservation of Antarctic marine living resources'.[32] Indicator species include Adélie penguins (*Pygoscelis adeliae*) and crabeater seals (*Lobodon carcinophagus*).

CCAMLR now considers and adopts a range of conservation measures, including those that protect the general marine environment, species and communities, and those that manage commercial fishing activities. The precautionary approach adopted by CCAMLR requires that conservation and management measures are established so that populations of harvested species do not decrease in size below levels that ensure stable recruitment. CCAMLR also encourages national programs operating in Antarctica to undertake fisheries-related research aimed at maintaining stocks of harvest species at levels that allow the greatest possible recruitment into populations of target species.[33]

The Convention on the Conservation of Antarctic Marine Living Resources was the first international convention whose fisheries management strategy was based on the ecosystem approach. It has successfully implemented this tactic in new, as well as established, fisheries. Until recently, fishing for Antarctic krill in the Southern Ocean has remained well below set catch limits. How well the current management strategy will function when the fishery expands remains to be seen.

1.4 Australian Antarctic Territory

Australia's interest in the southern continent began in 1911 when Sir Douglas Mawson led an expedition to Commonwealth Bay to conduct a variety of scientific studies that included discovering the magnetic South Pole. From 1929–31, Mawson returned to East Antarctica on the British, Australian and New Zealand Antarctic Research Expedition, during which he claimed 42% of the continent as Australian territory. Today, the Australian Antarctic Territory (AAT; Figure 7.1) comprises all land and islands south of 60°S and extends from 45°E to 160°E, with the exception of the French Territory of Adélie Land (136–142°E). The AAT covers some 5.95 million km^2, with ice shelves and ice tongues comprising another 0.14 million km^2.



AAT = Australian Antarctic Territory; ARG = Argentina; AUS = Australia; FRA = France; GBR = Great Britain; NOR = Norway; NZ = New Zealand; ZAF = South Africa

Source: Adapted from a map provided by the Australian Antarctic Data Centre

Figure 7.1 Antarctica and the Australian Antarctic Territory

The AAT coastline extends over 11 200 kilometres (excluding offshore islands). Only 1110 kilometres or 10% of the coastline is exposed rock. Some parts of the rock coastline are very steep, such as the Scullin Monolith, and only few areas offer the opportunity for establishing scientific research stations on ice-free rock. Thus, while the total area of the AAT is vast, the region of operation is comparatively small and human activities are concentrated on small areas where the impacts can be significant.

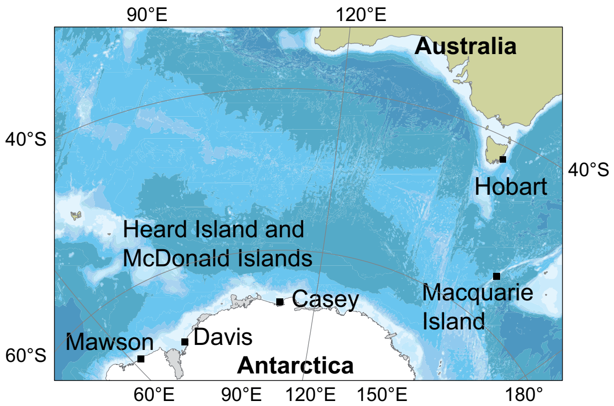
Australia works actively within the international forums of the Antarctic Treaty System to pursue its Antarctic interests. The Australian Government has retained a keen interest in Antarctica and has declared four goals for the Australian Antarctic Program:[b]

1 To maintain the Antarctic Treaty System and enhance Australia's influence in it.

2 To protect the Antarctic environment.

3 To understand the role of Antarctica in the global climate system.

4 To undertake scientific work of practical, economic and national significance.



Sources: Map provided by the Australian Antarctic Data Centre; additional data from Intergovernmental Oceanographic Commission et al.,[34] Antarctic Digital Database version 5, © Scientific Committee on Antarctic Research 1993–2006

Figure 7.2 Operational area of the Australian Antarctic Division

The AAT is administered by the Australian Antarctic Division of the Australian Government Department of Sustainability, Environment, Water, Population and Communities. Australia maintains a permanent presence in Antarctica through three continuously occupied continental stations, a station at Macquarie Island, and temporary field stations (Figure 7.2). Priority scientific research is conducted in diverse areas of Antarctic science on land and at sea. The goals and priorities of the scientific work are set out in the Australian Antarctic Science Strategic Plan 2011–12 to 2020–21.[c]

1.5 In this chapter

This chapter presents information on matters that affect the Antarctic environment and that describe the current state of the environment. The focus is on the AAT, because this is where Australia's activities are centred—although certain trends in the environment may relate to East Antarctica in general, or Antarctica as a whole. Also discussed are Australia's subantarctic island groups—Macquarie Island, and Heard Island and McDonald Islands—and the Southern Ocean.

Discussing every aspect of the Antarctic environment comprehensively is beyond the scope of this chapter. Instead, it reports on a number of selected indicators, some of which have long-term (more than one decade) data, and offer the best representation of current change in high-priority areas. The discussion identifies and considers environmental variables that are currently subject to pressures that are likely to become influential in the foreseeable future. This chapter aims to set a benchmark for future monitoring of environmental change and the outcomes of management actions by summarising indicators discussed in recently published scientific literature, as well as offering information on operational indicators that are relevant to running Australia's Antarctic program. Although only a limited number of sites are monitored regularly in the AAT, some results are representative of other areas in East Antarctica with similar ecological characteristics. Where appropriate, comparisons are made with events occurring in West Antarctica, where environmental change is proceeding at a faster rate than in the eastern part of the continent.

b www.antarctica.gov.au/about-us

c www.antarctica.gov.au/science/australian-antarctic-science-strategic-plan-201112-202021

State and trends of the Antarctic environment

In a rapidly changing world, environmental assessment requires long-term data to enable a comparison of the different states a natural ecosystem can achieve, and to determine trends of various parameters or indicators sensitive to possible change. For example, many vertebrate populations need to be monitored for two or three generations to establish the extent of natural fluctuations.[35] Moreover, because of the local differences in environmental conditions, it is important to monitor comparable indicators at more than one site to study the abilities of systems or organisms to adapt to changing conditions. It is also important to establish the processes that regulate and sustain a system. However, long-term data are often lacking; when they are available, they may be limited in their spatial scales and quality. The following section provides information on a number of key indicators important to the Antarctic environment, based on the available data.

At a glance

The physical and chemical components of the Antarctic environment are changing on a region-specific basis. Recent studies suggest that rate of change is increasing, and East Antarctica, so long thought of as safe from climate change, is undergoing measurable change and may contribute significantly to sea level rise in the future.

The complex Antarctic food web is based on vast numbers of marine microorganisms, including bacteria, phytoplankton and zooplankton. Changes to the marine environment, including ocean acidification, will have a significant impact on these organisms, and since they are at the base of the food web, these changes will have profound effects throughout the Antarctic ecosystems.

Climate change and warming conditions are also supporting the movement of alien species into the region, where they may outcompete endemic species. For example, there is already evidence that king crabs are expanding their range and are moving south, where they will be a new predator for the local soft-shelled and no-shelled invertebrates.

Many subantarctic islands already harbour alien plant species, which often thrive and outcompete endemic species. Many also carry the legacy of introduced vertebrates, such as rabbits or pigs that were released onto the islands during the sealing years as food sources. Rats and mice also abound and can cause havoc among seabird colonies.

Some populations of seals and penguins that were slaughtered in huge numbers in the late 19th and early 20th centuries have recovered while others, especially the seabirds, still suffer great losses in commercial fishing operations. The greatest threat, however, may well be the bycatch in illegal, unregulated and unreported fisheries. Most whale species that visit the Southern Ocean are still on the Red List of Threatened Species of the International Union for Conservation of Nature.

2.1 The physical environment

The physical environment includes both the nonliving factors that characterise an ecosystem (e.g. weather patterns, ice coverage, atmosphere), and the processes that drive them (e.g. weathering of rocks, ozone depletion of the atmosphere).

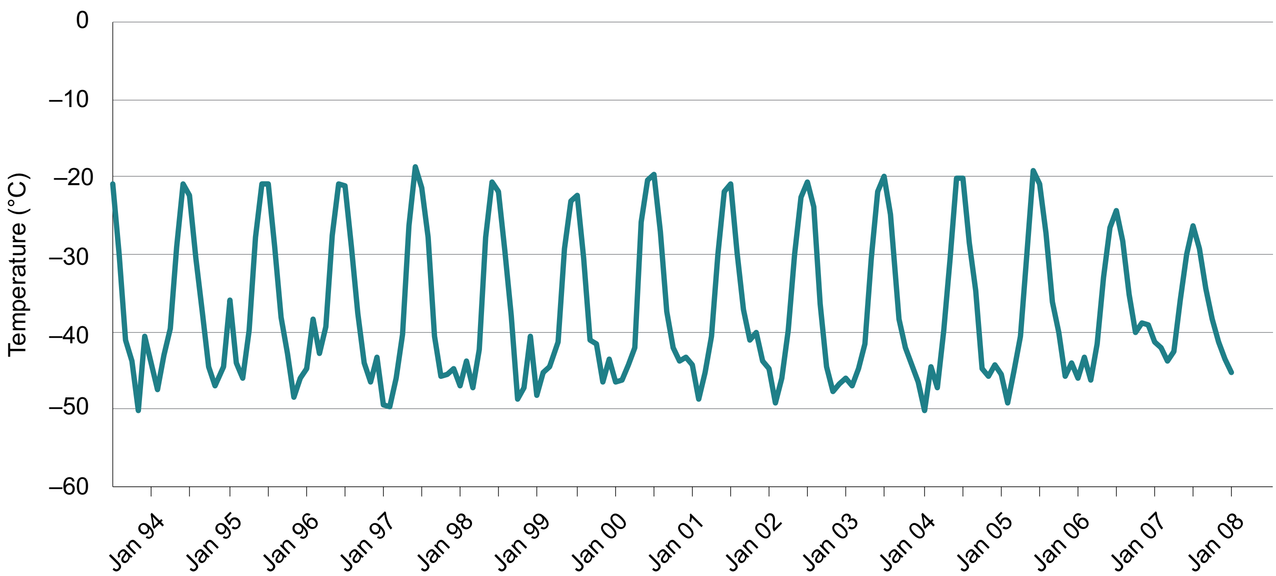
2.1.1 The atmosphere—climate and weather patterns

The climate of our polar regions and their dominant weather patterns are due to the shape of the planet. As Earth is spherical, the angle of incidence of solar radiation is shallower at the poles than at the equator. Thus, the same amount of sunlight is distributed over a larger area in the polar regions than at lower latitudes. The interior of Antarctica, where the ice sheet is 2–4 kilometres thick and hence high above sea level, remains very cold as it is generally well shielded from the warmer air masses found at the mid-latitudes

(Figure 7.3). In contrast, the equatorial regions, where seasonal change is barely apparent, remain warm all year round. This latitudinal pressure difference causes circulation patterns in the atmosphere that create cyclonic systems between 40°S and 70°S. The clockwise movement of the cyclones transports heat from the equator towards the Antarctic continent.[36] With the high elevation of the Antarctic ice sheet (average about 2200 metres),[37] the air above the continent cools significantly, becoming much denser than the air at the coast, and results in gravity-driven, strong katabatic winds (caused by local downward motion of cool air) in the coastal regions, where they are particularly prevalent during winter.

Although the atmosphere above Antarctica has been studied since the early 20th century, it is only in the past 30 years that increasingly detailed measurements have been available—albeit sparsely spaced. The Australian Bureau of Meteorology gathers year-round detailed weather information at all of Australia's Antarctic and subantarctic stations. Similar data are collected by other countries. In addition, weather data are gathered by automatic weather stations at more than 20 remote locations in East Antarctica, as well as by drifting buoys, balloons, and various satellite and ground-based remote sensing techniques.[2] While there is significant inter-annual variability in Antarctic weather due to various large-scale processes associated with the global movement of heat, trends are apparent in the historical and palaeoclimate records. In 2009, the Scientific Committee for Antarctic Research published a detailed assessment of the impact of climate change on the Antarctic environment, and a summary of the outlook for the continent and the Southern Ocean over the next century.[37]

Over the past half-century, the western and northern parts of the Antarctic Peninsula have warmed faster and to a greater extent than anywhere else on Earth; at the Vernadsky Station a statistically significant annual trend of +0.53 °C per decade occurred from 1951 to 2006. Winter temperatures at this site have an even stronger trend of +1.03 °C per decade. West Antarctica has warmed by approximately +0.1 °C per decade, particularly during winter and spring.[16,38] On the high plateau at the South Pole, a statistically significant cooling trend has been observed, which may be due to reduced penetration of weather systems to the pole. Coastal East Antarctica is warming less than West Antarctica.[16,37]



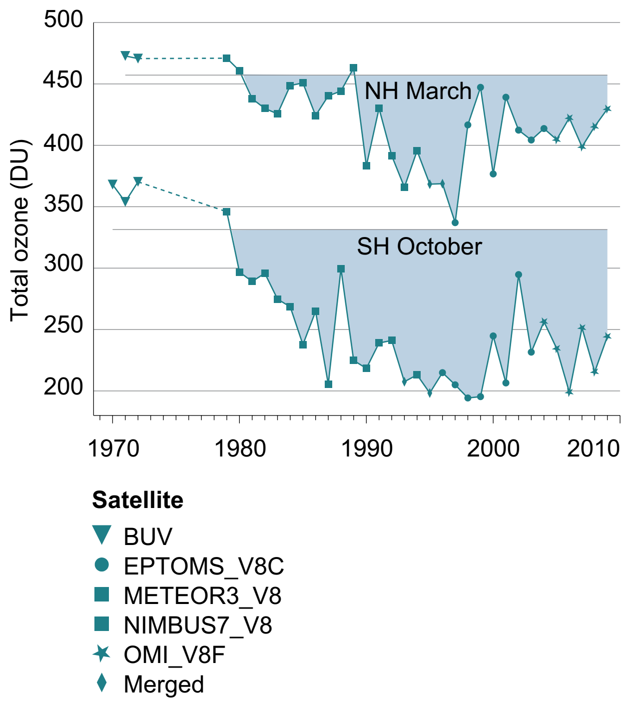
Source: Australian Antarctic weather station dataset, http://aws.acecrc.org.au/datapage.html, © Australian Antarctic Division

Figure 7.3 Mean time-weighted air temperature record 1 metre above ground level at Automatic Weather Station LGB35 (76°2'34"S, 65°0'0"E, elevation 2342 metres above sea level), January 1994 – July 2008

Balloon and satellite measurements indicate that the Antarctic lower troposphere (surface to 10-kilometre height) has warmed over the past 50 years,[37] while the lower stratosphere (10–30 kilometres) has cooled.[39] These temperature changes are very likely due to the effects of increased greenhouse gas concentrations in the atmosphere and, particularly in the case of the stratosphere, to decreases in ozone concentrations.[40]

The main variability of the atmosphere at southern mid and high latitudes is associated with the southern annular mode (SAM). This is a see-sawing of pressure levels between mid and high latitudes that operates on seasonal and inter-annual timescales around the entire Southern Hemisphere. Since the 1960s, the surface air pressure has decreased around the Antarctic coast but increased at southern mid-latitudes, producing a long-term trend in SAM. The trend has deepened the meteorological feature known as the Amundsen Sea Low, which resulted in the warming of the Antarctic Peninsula and to a lesser extent West Antarctica, and to a reduction of sea ice in these regions. Additionally, changes in SAM have led to fewer but more intense cyclonic weather systems in the Antarctic coastal region (60°S–70°S), except in the region of the Amundsen and Bellingshausen seas.[37]

Recent findings[37,40-41] show that the trend in SAM is largely due to atmospheric circulation changes that have been brought about by the 'ozone hole'—the anomalous reduction of the amount of ozone in the lower stratosphere (12–20 kilometres in altitude) above Antarctica that has occurred each spring since around 1980 (Figure 7.4). The destruction of ozone is caused by chemical processes involving human-made halon gases, particularly chlorofluorocarbons (CFCs), which are promoted by the extreme cold and special circulation conditions in the Antarctic stratosphere during winter. The ozone hole led to an increase in the damaging ultraviolet radiation received by Earth and also a cooling of the stratosphere. Each year, ozone levels are depleted in late winter to early spring, reducing temperatures of the Antarctic stratosphere during spring. The consequences of the cooling are changes in the lower atmosphere leading to a polewards shift of about 300 kilometres of the jet stream (strong winds 7–12 kilometres above Earth's surface), which in turn influences the route of storms in the high to mid-latitudes. The wind changes have been linked to regional changes in precipitation,[42] increases in sea ice around Antarctica,[37] warming of the Southern Ocean,[37] a local decrease in the ocean sink of carbon dioxide[40] and influences on the circulation in the mesosphere.[43]



NH = Northern Hemisphere; SH = Southern Hemisphere
Source: World Meteorological Organization[40]

Figure 7.4 Average total column ozone in dobson units (DU) for 63°S–90°S latitude in October for the Northern Hemisphere and Southern Hemisphere

Symbols indicate the satellite data that have been used in different years. The horizontal lines represent the average total ozone for the years before 1983 in March for the Northern Hemisphere and in October for the Southern Hemisphere.

Restrictions on the use of CFCs and other ozone depleting substances were negotiated internationally when the Montreal Protocol was signed in 1987. This treaty has since been ratified by 196 states and has led to a gradual reduction in equivalent effective stratospheric chlorine, which is an estimate of the effective quantity of halogens in the atmosphere. This estimate is used to quantify the depletion of ozone in the stratosphere. The levels of CFCs peaked in the mid-1990s; since then, the use of

these chemicals has been greatly reduced and Antarctic ozone levels appear to have increased by approximately 15%.[44] Since about 2000, the ozone hole has not increased in size. Although ozone levels are expected to fluctuate from year to year,[44] they are expected to recover in the middle of this century,[40] and over the remainder of the 21st century the surface changes brought about by ozone loss are expected to gradually relax.[44]

However, two recent studies report that the effects of the reversal of the ozone hole may be countered by increases in the concentrations of greenhouse gases, at least during the southern summer.[45-46] While the jet stream should return to the same latitude where it occurred before the ozone depletion, increasing greenhouse gas concentrations may cancel out the effects of the ozone recovery and the jet stream may stay at its current latitude. The interactions of these two competing events are not yet fully understood and much will depend upon the speed of the ozone recovery and the rate of increase of greenhouse gases.[45-46]

The El Niño Southern Oscillation (ENSO) is a large-scale mode of atmospheric and oceanic variability that is mainly situated in the low latitude Pacific Ocean region. It is associated with pooling of warm water alternately on the western and eastern Pacific Ocean every few years. ENSO does provide a contribution to climate variability in coastal Antarctica, but there is currently no evidence that this influence is changing in the long term.[37]

An iceberg and new sea ice, Antarctica
Photo by Doug Thost

7.1 Assessment summary

State and trends of the Antarctic atmosphere

Component	Summary	Assessment grade Very poor / Poor / Good / Very good	Confidence In grade	Confidence In trend
Surface temperature	Long-term measurements exist only at a limited number of sites (primarily since 1957), and large-scale analyses have used satellite thermal infrared data The temperature increase in the West Antarctic Ice Sheet has been 0.1 °C per decade			
Tropospheric temperature (surface to tropopause; 0–10 km above ground in polar regions)	Satellite and radiosonde measurements are available; most extensive and reliable data have been available since the late 1970s The general warming trend, linked to human factors, is taking place in the lower troposphere; the trend decreases towards the tropopause			
Stratospheric temperature (tropopause to stratopause; 10–50 km in polar regions)	Satellite and radiosonde measurements are available; most extensive and reliable data have been available since the late 1970s The general cooling trend is most significant over the Antarctic continent in spring and summer due to annual formation of the ozone hole			
Mesospheric temperature (stratopause to mesopause; 50–85 km)	Limited satellite and ground-based remote sensing data are available; however, there is some evidence of decreasing temperatures, but modes of variability make the interpretation complex	?		
Greenhouse gas concentrations (troposphere)	There are few tropospheric measurement sites in Antarctica and the subantarctic, but increases in carbon dioxide and methane linked to human factors are apparent			

Component	Summary	Assessment grade (Very poor / Poor / Good / Very good)	Confidence: In grade	Confidence: In trend
Stratospheric ozone concentration	There are possible signs of recovery (increased concentration of ozone) in spring and summer over Antarctica, but there is also significant inter-annual variability due to meteorological factors Stronger signs of ozone recovery are expected over the next decade or two	Good; Stable	Adequate high-quality evidence and high level of consensus	Adequate high-quality evidence and high level of consensus
Effective equivalent stratospheric chlorine	Improvement (decrease) in ODSs is expected in the troposphere Estimates of EESC in the stratosphere are based on the level of tropospheric ODSs combined with transport modelling; however, few measurements of EESC are available	Good; Improving	Adequate high-quality evidence and high level of consensus	Adequate high-quality evidence and high level of consensus

Recent trends: Improving; Deteriorating; Stable; Unclear

Confidence:
- Adequate high-quality evidence and high level of consensus
- Limited evidence or limited consensus
- Evidence and consensus too low to make an assessment

Grades:

Very good	Component unaffected by pressures
Good	Component affected by pressures and likely to recover in future
Poor	Component affected by pressures and trends likely to continue
Very poor	Component affected by pressures and unlikely to recover in future

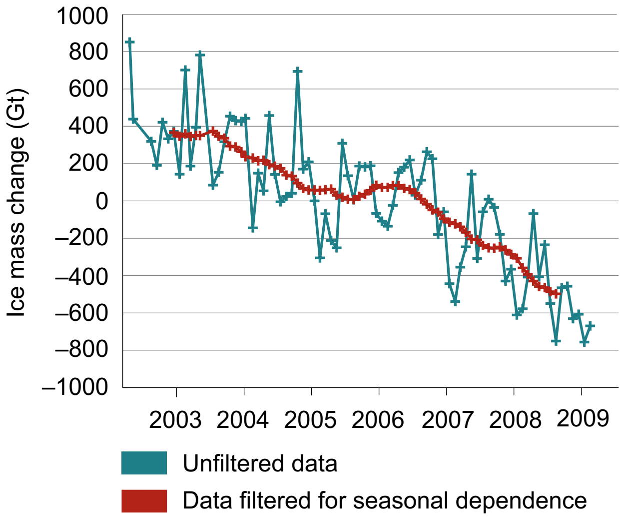
EESC = effective equivalent stratospheric chlorine; km = kilometre; ODS = ozone depleting substance

2.1.2 The cryosphere—Antarctic ice sheet and glaciers

The Antarctic ice sheet consists of three topographically different regions: the Antarctic Peninsula, which reaches further north than any other area in Antarctica; the West Antarctic Ice Sheet (WAIS); and the East Antarctic Ice Sheet (EAIS), which is by far the largest component, extending from about 30°W to about 165°E.

The ice mass budget of the Antarctic continental ice sheet is the balance between mass gained from snow fall and mass lost by melt and discharge as icebergs at the coast. The net mass balance is complex to assess because changes in snow fall and iceberg discharge vary by region and are not uniform across the continent. In some coastal regions abrupt changes have been observed, including the rapid disintegration of floating ice shelves, and this has raised questions about the potential for rapid ice discharge from Antarctica into the sea. The major environmental consequences of changes in the Antarctic ice sheet are to global sea level and to the freshwater input to the Southern Ocean, with possible flow-on effects to global ocean circulation and marine ecosystems.

Based on measurements from the Gravity Recovery and Climate Experiment (GRACE) satellites, which determine the weight of the ice sheet from space, Rignot et al.[47] report that the entire Antarctic ice sheet may have a net loss of 150 ± 75 billion tonnes per year (this is equivalent to a sea level rise of 0.4 millimetres each year), and that this rate is accelerating (by 14.5 ± 2 billion tonnes each year) (Figure 7.5). They claim that the loss estimate is supported by separate estimates of snow fall and ice discharge—the input–output method. However, the timespan of these observations is short, and there are considerable uncertainties in the observations. It is important to note that the observed net loss in ice mass is despite an overall thickening of the interior of East Antarctica by 1.8 ± 0.3 centimetres per year, measured by satellite radar altimetry from 1992 to 2003, which has been attributed to increased snow fall.[48] This increase in snow fall is consistent with a warmer atmosphere, which leads to more evaporation from the ocean.[48-49] Hence, increased snow fall on the interior of the ice sheet is consistent with the predicted responses to global warming.



Gt = gigatonne

Source: Adapted from Velicogna[50] by permission of the American Geophysical Union, © American Geophysical Union 2009

Figure 7.5 Ice mass changes for the entire Antarctic ice sheet, April 2002 – February 2009

While there are regional differences, the overall trend is downwards. Unfiltered data are blue crosses. Data filtered for seasonal dependence are red crosses.

In West Antarctica, GRACE satellite observations indicate that 132 ± 26 billion tonnes of ice per year are lost.[51] The WAIS is predominantly resting on bedrock that is far below sea level, and which is widely expected to make it vulnerable to global warming. The WAIS has been thinning during the most recent decades; however, this was due to the increased discharge of ice by a number of glaciers rather than surface melt.[52] For example, the flow rate of the Pine Island Glacier in West Antarctica has recently accelerated. The glacier ice is thinning and its grounding line (where the continental ice begins to float) is retreating southward. This is attributed to warmer ocean waters that increase melting from the base of the floating ice. As the bedrock beneath the glacier becomes deeper south of the grounding line, it is argued that the melt could continue to accelerate, due to the effect of pressure further lowering the freezing point, and therefore further contribute to sea level rise.[53]

In contrast, the EAIS is believed to be relatively stable; it is larger and higher than the WAIS and there are currently not such clear signs of warming in East Antarctica as there are in the west. However, recent results from field measurements show that much of the EAIS is also below sea level, and that the ice in some coastal regions is thinning and losing mass. Measurements by the GRACE satellites indicate the coastal fringes of the EAIS have lost about 60 billion tonnes of ice each year since 2006 (again with considerable uncertainty: 57 ± 52 billion tonnes of ice per year)[51] and that the annual loss has increased over the short measurement period.[50-51] Satellite measurements of the elevation of the ice sheet surface also show that the ice sheet is thinning near the coastal margins in a few locations in East Antarctica, particularly in the Totten Glacier and Cook Ice Shelf regions, indicating ice discharge is exceeding input. This is in general agreement with the regions of East Antarctic loss indicated by GRACE. The bedrock topography beneath East Antarctica is only recently being revealed from airborne surveys, with recent studies showing that the bedrock in the Totten Glacier catchment is largely below sea level.[54] Further inland, as much as 21% of the Aurora Basin, Wilkes Land region, is more than 1000 metres below sea level.[55] Further investigations of the depth and the bedrock slopes will determine the response of thinning at the margins to the ice mass balance of the region.

The influences of climate change on Antarctica are also illustrated by events in the Antarctic Peninsula region. The Antarctic Peninsula has experienced one of the highest regional temperature increases on the planet (2.8 °C in 50 years). Several floating ice shelves in that region have recently collapsed abruptly; for example, the Larsen B Ice Shelf collapsed in March 2002, and the Wilkins Ice Shelf started to disintegrate in March 2008.[16,56] By 2009, the Antarctic Peninsula had lost about 28 100 km^2 from the 152 200 km^2 of ice shelves present in the 1950s.[14] With the buttressing effect of grounded ice sheets gone, glaciers adjacent to the collapsing ice shelves now flow around three to four times faster into the ocean since the shelves disintegrated.[57-58] This increase in the discharge of grounded ice from the ice sheet to the ocean is contributing to sea level rise.

Glaciers at subantarctic Heard Island are also retreating. For example, the areal extent of Brown Glacier decreased from approximately 6.2 million square metres in 1947 to 4.4 million square metres in 2004, a 29% loss of its original area. Measurements in 2000 and 2003 reveal the recent rate of ice loss of this glacier is more than double the 57-year average from 1947–2004.[59]

2.1.3 The cryosphere—sea ice

Sea ice plays a key role in ocean–atmosphere interactions, global ocean circulation and the global climate system by forming an insulative, high-albedo cover (reflective of solar radiation) over a vast, although seasonally variable, area of the Southern Ocean (of around 3–19 million km^2). It strongly influences the ocean and ecosystems through the injection of brine during its formation and fresh water when it melts.[60] Being closely associated with patterns of atmospheric and oceanic temperature and circulation, sea ice responds sensitively to climate change and variability, and is also a key modulator of change and variability. It also dominates the seasonal physical and chemical dynamics of the high-latitude Southern Ocean and plays a major role in structuring high-latitude marine ecosystems. It follows that any substantial change in sea ice coverage will have potentially complex and wide-ranging impacts (Box 7.1), although the task of tracking environmental and biological consequences is immense and complex.[61]

There has been a small increase in the net areal extent of sea ice around Antarctica over the past 30 years (based on satellite data analysis),[62] although this result has recently been called into question.[63] However, undisputed regional changes are occurring in the Antarctic sea ice cover in response to changing patterns of large-scale atmospheric circulation. Most notable are the strong reductions in the sea ice extent west of the Antarctic Peninsula in the Bellingshausen Sea, and the strong increases in sea ice extent in the Ross Sea.[64] In the western Antarctic Peninsula region there is mounting evidence that a decreasing ice season duration has affected multiple levels of the marine food web.[65-66] The sea ice signal in the East Antarctic sea ice zone is mixed and complex,[64,67] but has shown only minor changes over the satellite record, consistent with natural variability.

Box 7.1 Recent Antarctic sea ice change and variability, and their implications

Antarctic sea ice forms a highly reflective insulating 'skin' over much of the Southern Ocean. It expands from 3–4 million square kilometres each summer to about 19 million square kilometres each September–October.[68] Sea ice and its accumulated snow cover are very important for both climatic and biological systems. Sea ice formation is a driver of global ocean circulation and is also a habitat for algae, which forms the base of the Antarctic food web. Consequently, significant changes in the amount of sea ice formed each year will impact the climate, biology and ecology of Antarctica and the Southern Ocean, with potentially significant global consequences.

Over the era for which satellite imagery of sea ice is available (1979 to present), the areal extent of sea ice has increased at a small but statistically significant rate of approximately 1% per decade.[62] However, of much greater significance are the regional changes observed. Increases in the Weddell Sea sector have been around 1% per decade, 0.9% per decade in the West Pacific Ocean sector, 2.1% per decade in the Indian Ocean sector,[62] and the largest increase has been in the Ross Sea with 5% per decade. In contrast, the Amundsen–Bellingshausen seas have lost sea ice at 7% per decade. Moreover, proxy records derived from analysis of ice sheet core and historical whaling records suggest that sea ice coverage may have declined substantially in certain regions since the late 1950s and early 1960s.[69-70] It is apparent from the satellite passive microwave data records that substantial seasonal and decadal variability is superimposed on longer term trends in all sectors.

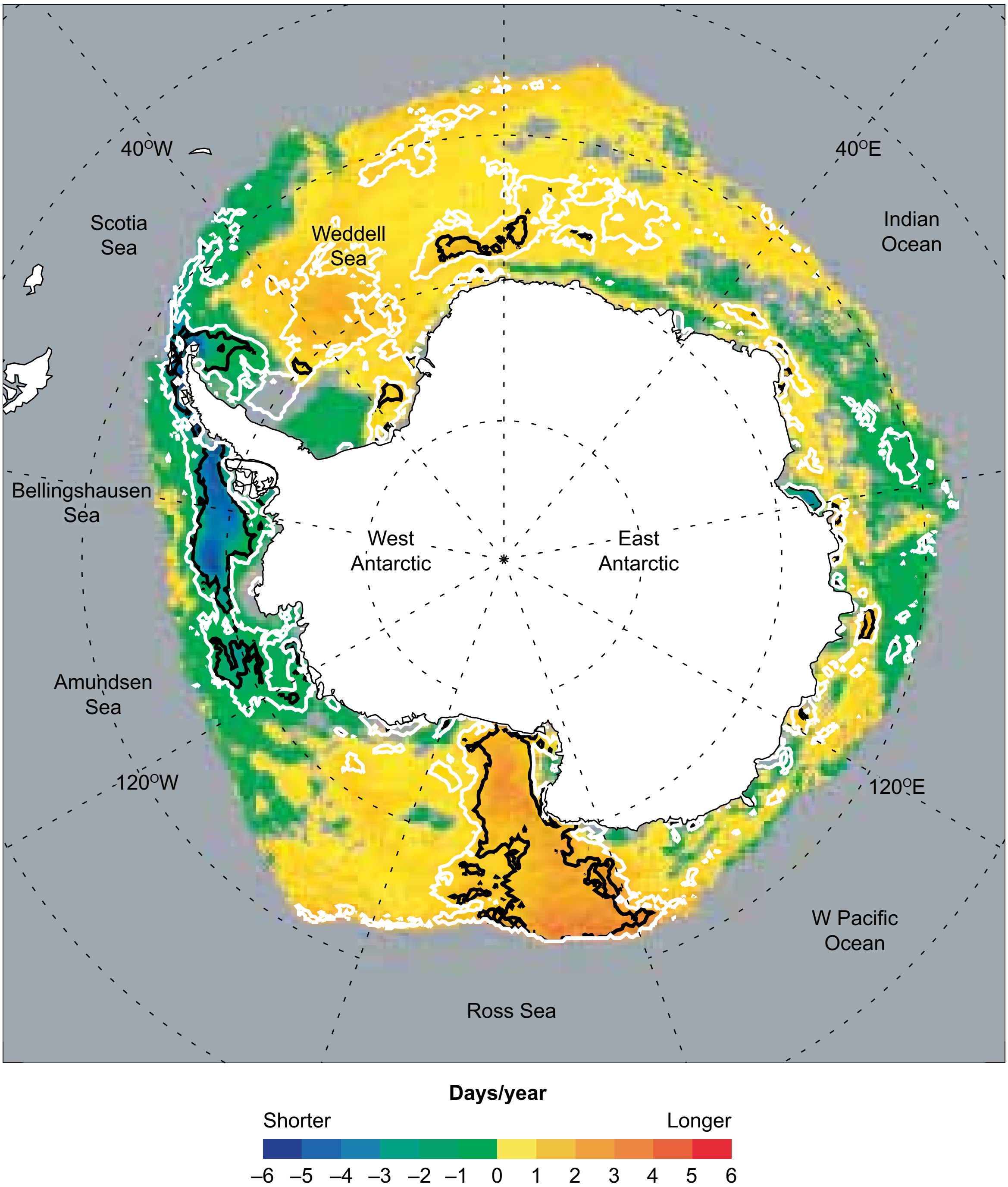
The seasonality of the sea ice coverage (formation and retreat) has also changed, but again with large differences between regions,[64,71] especially in West Antarctica (Figure A). In the north-east and west Antarctic Peninsula and in the Bellingshausen Sea, the sea ice season has shortened by about 85 days from 1979–80 to 2004–05. These changes are probably due to changes in large-scale modes of atmosphere circulation affecting regional winds and temperatures,[64] although other factors, such as the recent incursion of relatively warm waters onto the continental shelf, may also have been a factor in the weakening of ice shelves.[72]

In contrast, sea ice in the western Ross Sea now persists for about 60 days longer than in 1979.[68] In East Antarctica, the sea ice zone is narrower than in West Antarctica. The large sea ice area and the longer season are linked to lower surface temperatures[68] and an increase in the occurrence of more southerly winds. Complex patterns of change have been observed in both the timing and extent of the seasonality of sea ice across the region from 1979 to 2009, with sea ice persisting for one to two days more per year (R Massom, University of Tasmania, pers. comm., May 2011). In the Prydz Bay region, sea ice persists for two to three days more per year.

While observations show sea ice extent is increasing slightly over time, current models predict that Antarctic sea ice will decrease in extent by 24%, and 34% by volume, by 2100,[73] highlighting the need to understand the current conditions and how sea ice impacts the biological components of the Southern Ocean ecosystem. For example, fast ice is an important habitat for sea ice algae and microorganisms, and a breeding platform for Weddell seals and emperor penguins. Increased fast ice extent or duration can negatively affect breeding success. Pack ice, the area where many top predators forage, is influenced by snow fall and surface flooding. Changes in sea ice and wind regimes, light availability and mixed-layer depth of oceanic waters affect phytoplankton communities, which in turn affect food availability for these predators.

Fieldwork within the Australian Antarctic Program provides crucial and essential information on sea ice, biological and biogeochemical processes and properties, and is an important means of validating key satellite data products, including sea ice thickness, which remains difficult to measure accurately around Antarctica (photo © Tony Worby, courtesy Australian Antarctic Division)

Box 7.1 *continued*



Source: Adapted from Stammerjohn et al.[64] by permission of the American Geophysical Union, © American Geophysical Union 2008

Figure A Trend map of Antarctic annual sea ice duration (in days/year) derived from satellite passive microwave data for the period 1979–80 to 2004–05

The black/white contours delimit 0.01–0.10 significance levels, while grey shading within the sea ice zone signifies a near-zero trend.

7.2 Assessment summary

State and trends of the Antarctic cryosphere

Component	Summary	Assessment grade (Very poor / Poor / Good / Very good)	Confidence: In grade	Confidence: In trend
Sea ice extent	Antarctica-wide since 1960 (the start of the modern satellite era): 1.2 ± 0.2% increase per decade with regionally opposite trends; 7.1 ± 0.9% decrease per decade in Amundsen–Bellingshausen seas, 4.9 ± 0.6% increase per decade in Ross Sea There is more certainty about the observations than about the environmental consequences; however, proxy information from ice core and historical whaling records suggests that a major decline in sea ice coverage occurred in the decades before the the late 1950s to early 1960s	?		
Sea ice seasonality	There are major and opposing trends in different areas. In the West Antarctic Peninsula and north-west Weddell Sea, later annual advancing of sea ice edge and earlier retreat means the sea ice season is shortening, with deleterious effects on ecosystems; sea ice advance appears more sensitive to climate variability than sea ice retreat. Conversely, there is a longer season in the western Ross Sea. There is no clear trend in seasonality for East Antarctica, where the pattern of change is complex			
Pack ice (ice floes of varying sizes and density) characteristics	Changes to the characteristics of pack ice are likely to have a cascading impact through the ecosystem. At present, there is great uncertainty in large-scale estimates of the thickness distributions of sea ice and its snow cover. Research is under way to derive these key quantities from satellite data			
Fast ice (sea ice adjacent to land)	There is insufficient information about the seasonality of fast ice (current satellite-derived timeseries is too short and limited to East Antarctica for 2000–08). From 2000–08, there were different responses in the Indian Ocean and West Pacific sectors			

Component	Summary	Assessment grade (Very poor, Poor, Good, Very good)	Confidence (In grade, In trend)
East Antarctic Ice Sheet (EAIS)	There is mounting evidence that the EAIS is losing mass, although by how much is uncertain. Continent-wide, there are also signs of acceleration in the loss rates, although the timespan of comprehensive observations is short. Lack of in situ data on glacial isostatic adjustment (uplift) limits interpretation of observations of ice sheet mass and elevation change. Net mass loss contributes to global sea level, and changes the freshwater budget of the Southern Ocean		
Heard Island and other subantarctic glaciers	Most Heard Island glaciers have retreated since 1947: total glacier area decreased (from 288 km^2 in 1947 to 231 km^2 in 1988); for 2000–03, ice loss of Brown Glacier is estimated at around 8.0 × 10^6 m^3/year, more than double the average of the last 57 years Rising temperatures and newly exposed terrain led to changes in distribution of flora		

Recent trends: Improving; Stable; Deteriorating; Unclear

Confidence:
- Adequate high-quality evidence and high level of consensus
- Limited evidence or limited consensus
- Evidence and consensus too low to make an assessment

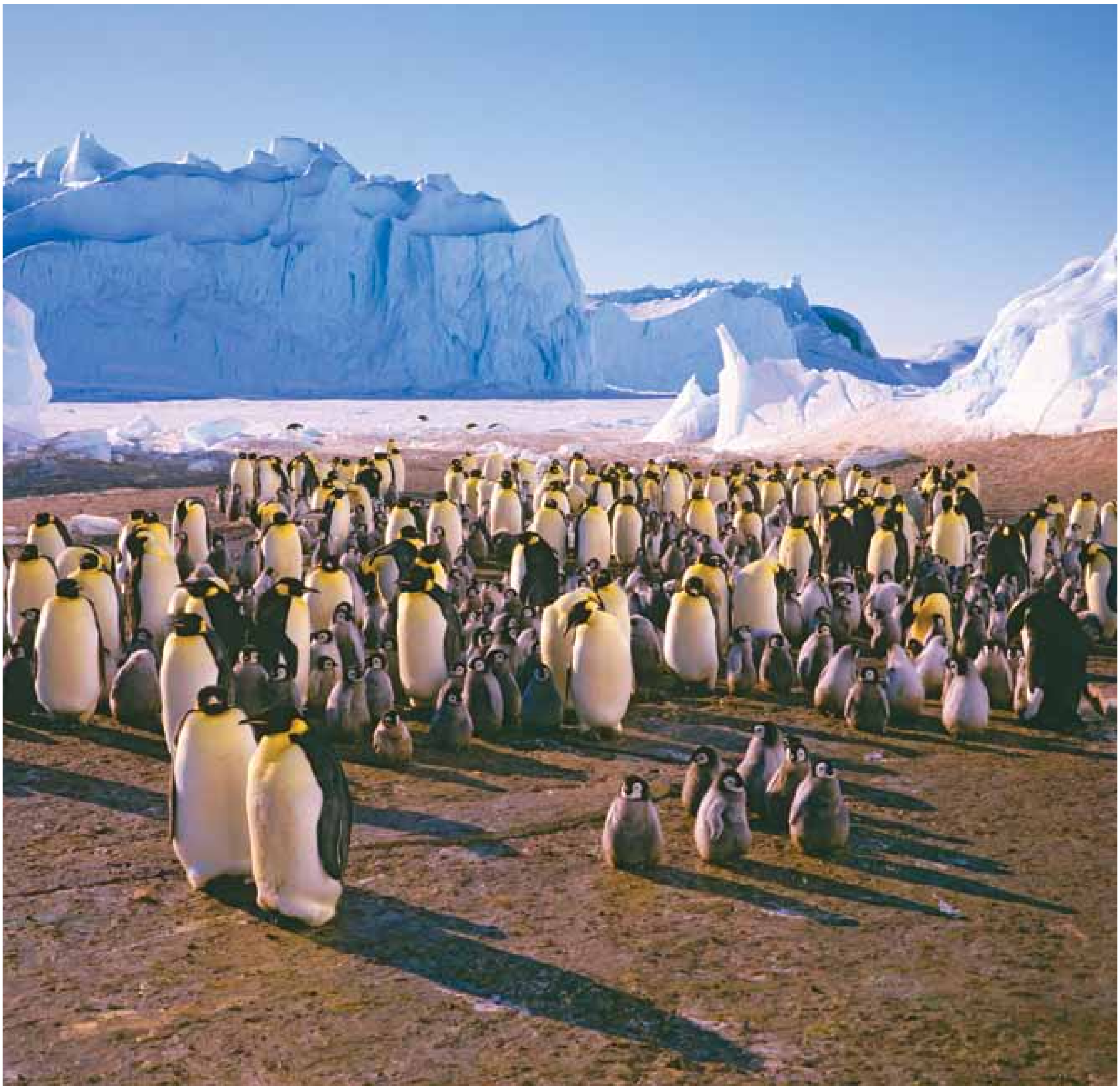
Grades:

Very good	There are no significant changes in physical or chemical processes
Good	There are some significant changes in physical or chemical processes in some areas, but these are not to the extent that they are significantly affecting ecosystem functions
Poor	There are substantial changes in physical or chemical processes and these are significantly affecting ecosystem functions in some areas
Very poor	There are substantial changes in physical or chemical processes across a wide area of the region as a result of human activities, and ecosystem functions are seriously affected in much of the region

km^2 = square kilometre; m^3 = cubic metre

2.2 The Southern Ocean

The Southern Ocean is the only ocean that encircles the globe uninhibited by land masses. It flows around Antarctica, connecting the world's major southern ocean basins, and also links the surface of the ocean with the deepwater layer.[74] The Southern Ocean covers an area of approximately 20.3 million square kilometres. Much of its area is 4000–5000 metres deep and its temperatures are below 0 °C. Various currents form the Southern Ocean. The major current in the Southern Ocean is the Antarctic Circumpolar Current, which flows mainly eastwards, although important north–south movements also occur in various water masses. The structure of the water current system is still being investigated. Recently, measurements of a deep current system 3 kilometres below the surface and flowing along the Kerguelen Plateau in the southern Indian Ocean found that more than 12 million cubic metres of cold water are transported here each second.[75] This system—the Kerguelen Deep Western Boundary Current—makes a significant contribution to global ocean circulation as these deep currents transport Antarctic waters into deep layers of the major ocean basins.



Emperor penguin (*Aptenodytes forsteri*) colony, near Mawson Station, Antarctica
Photo by Graham Robertson

In winter, the surface of the ocean bordering the Antarctic continent freezes. The exceptions are a few areas, called polynyas, where persistent katabatic winds, formed by cold air draining from the interior of the continent, blow from the land to the sea and keep the sea surface clear of ice. When sea ice forms, salt is forced out of the forming ice (brine rejection) making the water below this ice denser and more saline.[60] The densest water mass of the Southern Ocean is the Antarctic bottom water, which forms in only a few locations near the Antarctic continent. Antarctic bottom water is derived from shelf waters that are dense, cold and oxygen rich. The bottom water spills over the edge of the continental shelf and reaches deep oceanic waters that move northwards along the ocean bottom. The warmer waters in the north flow south and fill the gap, and as they reach higher latitudes they cool and sink.[76] Through this cycle of water movement and the connection of all major ocean basins, heat and other components are redistributed and make the bottom water a key driver in the world's 'conveyer belt' of ocean currents.[77] These processes influence weather, rainfall patterns and temperatures around the world.[13]

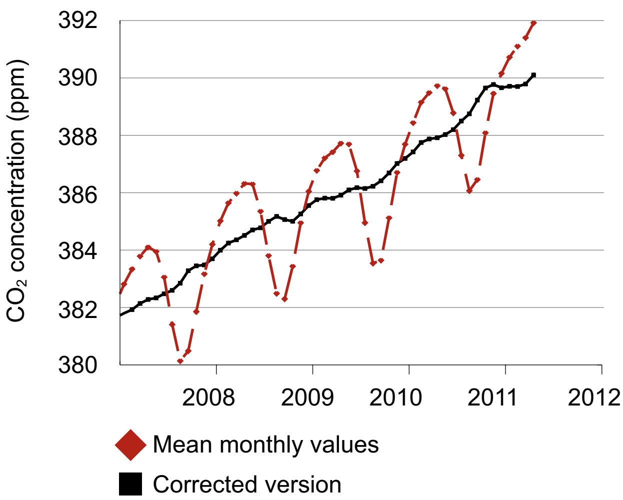
Although generally nutrient rich, the productivity of the Southern Ocean is not as high as may be expected due to low levels of iron (an important micronutrient) and low light levels (because of persistent cloud cover), particularly during the southern winter.

The Southern Ocean is the least well understood ocean due to its vast size and the difficulties in obtaining measurements in winter, because large areas are covered by ice. Nonetheless, some measurements have been possible: in the region of the Weddell Sea from 35°S to 65°S, the Southern Ocean has warmed by 0.17 °C in the upper 1000 metres since the 1950s.[78] This rate of warming is faster than anywhere else in the world.[74]

2.2.1 Ocean acidification

The Southern Ocean is one of the world's largest sinks for atmospheric carbon dioxide. Approximately 25–30% of the anthropogenic (caused by human activity) carbon dioxide released to the atmosphere has been taken up by the world's oceans—some 40% of which has been taken up by cold Southern Ocean waters that lie south of 40°S.[79-81]

While reducing the accumulation of carbon dioxide in the atmosphere, ocean uptake is making sea water more acidic. Current atmospheric carbon dioxide levels of approximately 391 parts per million are higher than they have been for at least the past 25 million years[82] and models predict it could rise to >1000 parts per million by 2100.[83-84] Compared with pre-industrial times (pre-1700s) when carbon dioxide levels were around 280 parts per million, the pH (measure of acidity) of the ocean has dropped from pH 8.2 to pH 8.1, indicating increased acidity.[85] Thus, although the ocean is still alkaline, its level of acidity is increasing. This drop in pH is linked to the dramatic rate of increase of carbon dioxide in the atmosphere—the rate is one hundred times greater than that during any other time in the past 650 000 years.[85] In the period from 2000 to 2004, the rate of global carbon dioxide emissions grew by 3.3% per year compared with 1% per year in 1990–99 (Figure 7.6).[84]



ppm = parts per million
Source: Conway & Tans[86]

Figure 7.6 Recent global monthly mean carbon dioxide (CO_2) concentration, 2007–11

In April 2011, the global average carbon dioxide concentration was 391.55 parts per million.
The red line shows the mean monthly values centred around the middle of each month; the black line is the corrected version based on a seven-month running average.

Ocean acidification is likely to affect the efficiency of the Southern Ocean as a sink for atmospheric carbon dioxide and will also have profound impacts on species and ecosystems (see Sections 2.3.1 and 3.1.1).

7.3 Assessment summary

State and trends of the Southern Ocean

Component	Summary	Assessment grade (Very poor / Poor / Good / Very good)	Confidence: In grade	Confidence: In trend
Sea surface temperature	Since 1950, the upper kilometre of the water column and densest part of Antarctic bottom water in the Weddell Sea warmed by 0.2 °C at 700–1000 metres between 35°S and 65°S	Good ↙	●	●
Ocean acidity	Polar pH levels are changing twice as fast as tropical ones; pre-industrial pH 8.2 dropped to pH 8.1, indicating increased acidity	Good ↙	●	●
Ocean salinity	The coastal waters between the Ross Sea and the southern Indian Ocean are fresher now than 50 years ago, making the Antarctic bottom water that forms here less saline	Good ↙	●	●
Southern Ocean circulation and structure	Increase in wind strength is expected to affect the ACC and upwelling of circumpolar deep water, formation of different water masses and gyre activity		○	○
Sea level	In December 2009, data were obtained from about 135 locations from 250 tide gauges, but large gaps still exist in datasets Sea level changes are not expected to be uniform across Earth. Sea level rise in the Southern Ocean south of the ACC is predicted to be less than in the Arctic		○	○

Recent trends
- ↗ Improving
- ↙ Deteriorating
- — Stable
- ? Unclear

Confidence
- ● Adequate high-quality evidence and high level of consensus
- ◐ Limited evidence or limited consensus
- ○ Evidence and consensus too low to make an assessment

Grades

Very good	There are no significant changes in physical and/or chemical processes as a result of human activities
Good	There are some significant changes in physical and/or chemical processes as a result of human activities
Poor	There are substantial changes in physical and/or chemical processes as a result of human activities that significantly affect ecosystem functions in some areas
Very poor	There are substantial changes in physical and/or chemical processes as a result of human activities that significantly affect ecosystem functions in much of the region

ACC = Antarctic Circumpolar Current

2.3 The living environment

Given its extreme conditions, the Antarctic comprises a perhaps surprising diversity of ecosystems. Antarctica is the coldest, windiest, driest and highest continent. Only about 0.4% of the continent is ice-free. Since plants and the invertebrates associated with them and most seabirds require bare rock as growth or breeding habitats, the ice-free areas are important for their survival; consequently, many species are often found breeding close to each other. Antarctica and the Southern Ocean, distinct in their physical properties from other parts of the world, have a large number of endemic species. For example, 100% of the nematodes, 50% of the lichens and more than 30% of the terrestrial invertebrates on the Antarctic continent are found nowhere else,[87] and the dominant fish species in the Southern Ocean are endemic to the region.[88]

2.3.1 Marine environments

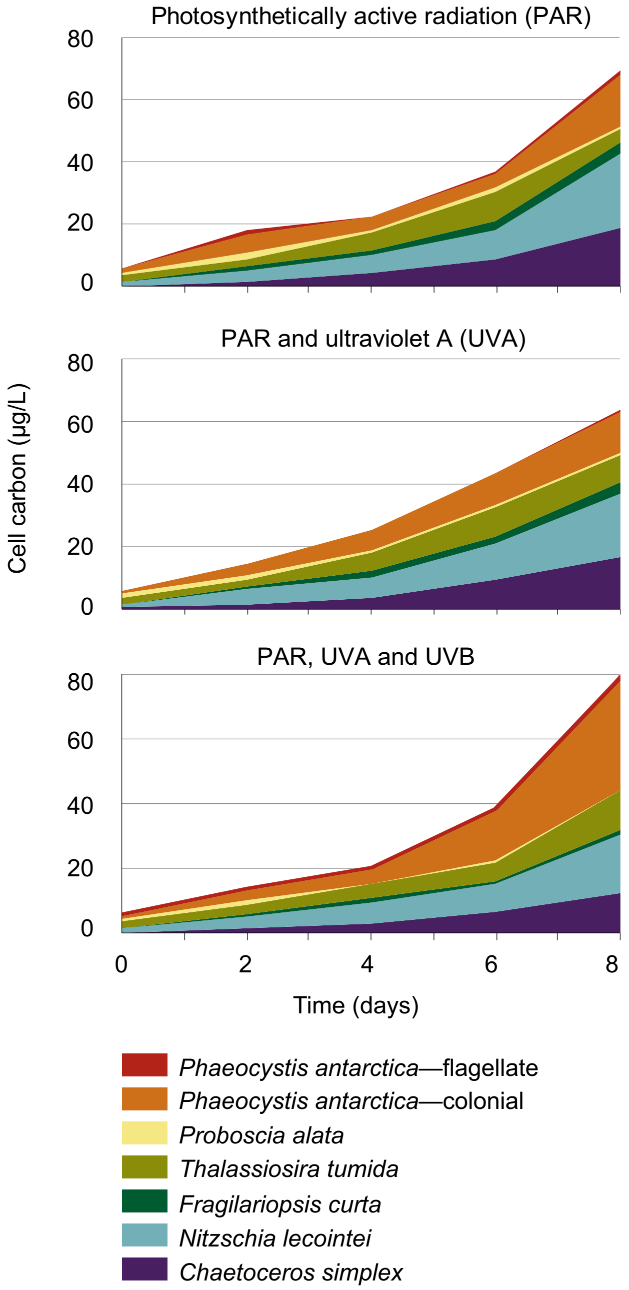
One of the likely results of climate change is an alteration in the distribution of species, as those adapted to warmer climes expand their ranges south. For example, crabs are not found in the ocean around Antarctica—they became extinct there some 15 million years ago.[89] Many invertebrate organisms, such as brittle-stars and molluscs, evolved to have only soft shells in the absence of predators. Others, such as some marine snails, have lost their shells altogether. These creatures are no match for shell-crushing invaders, such as king crabs. There is already evidence that king crabs are expanding their range and moving south. In 2004, four specimens of a king crab that is abundant in the coastal waters of New Zealand were found in the northern Ross Sea and near the Balleny Islands (approximately 67°S).[90] More recently, thousands of these creatures have been found on the shelf slope of the western Antarctic Peninsula.[91] Their presence alone has the potential to extensively modify species diversity in the region.

The pelagic environment

Marine microorganisms form the basis of Antarctic food webs. They include vast numbers of bacteria, phytoplankton (single-celled plants) and zooplankton (single-celled animals). Bacterial communities occur throughout the water column of the Southern Ocean, as well as in the sea ice. These tiny, single-celled organisms provide food for zooplankton, krill, fish and other vertebrates. They are exceptionally numerous and comprise around 90% of the living matter produced in Antarctic waters. The biomass of phytoplankton is estimated to be 5000 million tonnes; there are also about 1200 million tonnes of bacteria and some 600 million tonnes of protozoa.[92] The number of species for many groups of organisms is still unknown. The Census of Antarctic Marine Life found many new species that are still being identified; this is particularly true for bacteria.[93] The phytoplankton (diatoms, dinoflagellates, cilliates and other protists) in the Southern Ocean comprises 560 known species,[94] but only a few are widely dominant; their community structure is not constant throughout the Southern Ocean.[95] One group, the diatoms, is responsible for most of the primary production (fixing of inorganic carbon into organic molecules). Their level of productivity varies greatly with season, being highest in spring and early summer.[96] Most of their production is consumed or recycled by bacteria and protozoa.[97]

Intense phytoplankton blooms occur in Antarctic waters during spring and summer when increasing sunlight melts the sea ice and warms the ocean. The high light conditions and high nutrient content in the surface waters are ideal conditions for the growth of phytoplankton cells. During photosynthesis, phytoplankton take up carbon dioxide that dissolves in the ocean from the atmosphere. They also produce dimethyl sulfide, a natural aerosol, which is released into the atmosphere. Here it helps cloud formation as it acts as a cloud condensation nucleus,[98] and increases the reflectance of the sun's heat from Earth. Thus, these single-celled organisms not only support the food web, they also influence the biochemistry of the ocean and play a vital role in affecting global climate by reducing carbon dioxide in the atmosphere and altering global heat balance. In turn, they are affected by anthropogenic changes to the atmosphere. Ozone depletion has increased the damage they experience due to increased ultraviolet B radiation (Box 7.2). Anthropogenic environmental changes are likely to have far-reaching impacts on the Antarctic marine ecosystem.

Box 7.2 *Phaeocystis antarctica* and climate change



µg/L = microgram per litre

Source: Adapted from Davidson et al.[113]

Phaeocystis antarctica is among the most abundant phytoplankton species in Antarctic waters. It is one of the first species to reproduce in spring, when its blooms can dominate the phytoplankton community at the ice edge, as well as in deeper offshore waters.[99-100] This alga has a complex life history involving solitary cells and a colonial life stage. Individual cells give off much of their photo-assimilated carbon to form a colony matrix containing thousands of cells. These colonies offer protection from grazing, mediate trace metal dynamics, and are a repository of carbon that can be metabolised in the dark.[101-102] With some exceptions,[103] *Phaeocystis* spp. blooms are commonly remineralised in near-surface waters and contribute little to the vertical carbon export (movement of carbon from surface to deeper ocean waters).[104-106] *P. antarctica* also releases ultraviolet (UV)-screening compounds (Figure A), an antibiotic and large amounts of dimethyl sulfide (DMS).[107-108]

This alga has a significant effect on a number of ecosystem and physical processes because of its abundance and physiology. The peculiar physiology of this alga causes its blooms to strongly influence the structure and function of the plankton community.[109] It also plays a disproportionately large role in mediating global climate by affecting vertical carbon flux and enhancing cloud formation and solar reflectance (global albedo) via the release of DMS.[110-111] Climate change is predicted to increase stratification of surface waters, especially at high latitudes, trapping phytoplankton in shallow water where they are exposed to high UVB radiances (280–320 nanometre wavelength).[112] Competition experiments show that *P. antarctica* can outcompete other phytoplankton species, such as diatoms, in high UVB radiances.[113] Further research is required to determine *P. antarctica*'s tolerance of other predicted changes including temperature, salinity, nutrients and pH, and how changes may affect its role in the ecosystem.

Figure A Changes in species-specific biomass of phytoplankton grown in mixed culture under different ambient Antarctic light conditions

Zooplankton includes creatures like krill—small shrimp-like crustaceans that rank highly on the menu of many top predators, such as fish, whales, seals, penguins and flying seabirds. Krill in turn feed on phytoplankton and sometimes small zooplankton. Copepods (minute crustaceans) are another grazer on phytoplankton, making up most of the biomass in many pelagic zooplankton communities, and are an alternative food source for higher predators. Krill distribution and abundance were examined in 2006 during a major marine science voyage known as BROKE-West (Baseline Research on Oceanography, Krill and the Environment–West) in the western sector of East Antarctica. Transects were sampled from 30°E to 80°E and krill abundance in this region was estimated to be more than 2.6 million tonnes.[114]

Both phytoplankton and zooplankton comprise species that build shells made of aragonite or calcite. An increase in the acidity of the Southern Ocean is likely to first affect these planktonic species that form the base of the food web. Carbon dioxide–driven acidification reduces the availability of the carbonate ion that calcium carbonate shell-making organisms require for calcification, reducing the ability of these organisms to form shells. The rapid change in the acidity of the ocean is already affecting calcifying organisms—the shells of planktonic organisms known as foraminifera are now about one-third lighter compared with pre-industrial times.[115] However, the Australian Antarctic Division–led Southern Ocean Continuous Plankton Survey has observed very large blooms of foraminiferans, especially in the southern summer of 2004–05 when they dominated the surface plankton (up to 80% of abundance) through much of the Southern Ocean south of Africa to Australia.[116]

It is important to note that different species respond differently to environmental changes. While some are likely to be affected adversely, others might benefit from the changes.[117] However, changes at the base of the food web, such as to phytoplankton and zooplankton, can potentially radically change the dynamics of the Southern Ocean ecosystem, but it is still unclear whether (or how) higher order organisms are affected.

The benthic environment

The bottom of the Southern Ocean offers rich habitats on hard and soft substrata to a great number of species, many of which grow much slower than their temperate counterparts. Both fixed and mobile species including sponges, molluscs, sea stars and worms are highly diverse and abundant. Bryozoans are particularly diverse and have a high level of endemism.[23] Based on the outcomes of the Census of Antarctic Marine Life, the CCAMLR proclaimed two ‘vulnerable marine ecosystems’ to protect species assemblages and aid the conservation of biodiversity.[118]

At depth, environmental conditions are stable and species communities and assemblages appear not to change much. A threat to the biodiversity of the benthos is iceberg grounding. Icebergs break off glacier snouts and ice shelves and often get caught in currents that transport them away from their calving sites. In shallow water, icebergs can become grounded, which stirs up the sediment and crushes benthic fauna in the way. The damage caused by grounding icebergs tends to be local. So far, these grounding events appear to have contributed to the species diversity in the benthic communities by creating a patchwork of areas that are in different stages of recovery. However, an increased rate of iceberg calving may cause more frequent disturbances to benthic areas and not leave sufficient time for populations to recover. Fast-growing organisms are likely to have a better chance to resettle than slow-growing ones. In the long term, while the benthos may not remain scarred and unpopulated, its communities may change in their species composition and some organisms are likely to be lost, at least locally.

2.3.2 Terrestrial environments

Antarctic continent

Antarctica is almost entirely covered in permanent ice. Ice-free areas of exposed rock are rare and account for only about 0.4% of the total area. Most of the exposed rock is in remote mountain ranges; less than 6000 square kilometres is found in small, isolated patches adjacent to the coast but this provides habitat for most of the terrestrial biodiversity of Antarctica. Exposed, ice-free mountain tops exist inland, and about 40–50 species of mosses and lichens survive at elevations of 2000+ metres above sea level. Temperatures range from −30 °C in summer to about −70 °C in winter and the moisture content of the air

is typically very low (less than 0.5 kilograms per cubic metre).[119] Adélie penguins, and seabirds such as Antarctic petrels (*Thalassoica antarctica*) and snow petrels (*Pagodroma nivea*), use ice-free habitats for nesting, and some seals use coastal Antarctic beaches as haul-out areas and fast ice (sea ice adjacent to land) for breeding.

The coastal areas and offshore islands are largely south of the Antarctic circle (66°33'S), which marks the most southerly latitude at which the sun is above the horizon at the winter solstice. The climate here is defined as cold maritime. Milder than the interior, average temperatures can rise above 0 °C in summer but drop to less than –30 °C in winter. The region between 60°S and 70°S is the cloudiest on our planet, with a cloud cover of 85–90% throughout the year.[120] Winds generated in the interior of the continent drive cold, dense air towards the coast. Smooth ice surfaces on the ice plateau and steep slopes at the coast reduce friction and intensify katabatic winds, which are strongest at the edge of the continent (often 180 kilometres per hour or more). Terrestrial ecosystems are isolated from each other and their floral and faunal communities are less complex than those at lower latitudes[121] or the Arctic region. For example, there are 900 species of vascular plants in the Arctic[122] compared with 2 species in the Antarctic,[123] where lichens and mosses dominate the visible flora.

The microbiotic communities (bacteria and fungi) are species-rich in comparison to other communities and exist in lakes, moss cushions and the soil. Many microorganisms, such as diatoms and cyanobacteria, are endemic to Antarctica.[124]

Lakes and drainage systems are also part of the ice-free areas of Antarctica. Many of these systems exist close to the freezing point of water and their water levels and salinity react quickly to changes in the moisture content of the environment.[125] Changes in the water chemistry affect life in the lakes, which include bacteria, algae, viruses and some invertebrates, such as copepods and rotifers.

Icicles drip off an iceberg, Antarctica
Photo by Doug Thost

In researching the terrestrial environment, a number of important questions remain unanswered. These concern the species diversity and distribution of soil organisms, such as invertebrates, microbes and algae. New genetic techniques reveal an increasing complexity of species, for example among crustaceans, such as amphipods,[126] and bacteria.[127] How these organisms participate in the cycling of nutrients and the flux of carbon through the terrestrial systems is poorly understood. There is also insufficient knowledge about their contribution to the hydrology of terrestrial systems or feedback loops that link them to climate changes.[128] Box 7.3 discusses changes in Antarctic vegetation communities.

Subantarctic islands—Heard Island and McDonald Islands, and Macquarie Island

High-latitude islands and island groups are part of the Antarctic terrestrial environment. Terrestrial ecosystems of the subantarctic islands are very different from those of continental Antarctica. Surrounded by the Southern Ocean and located south of 50° latitude, they are mostly free of permanent ice, although Heard Island, situated south of the Antarctic Polar Frontal Zone has a permanent ice cover. Macquarie Island lies to the north of this zone. The seasonal temperature fluctuations are modest, with mean temperatures of around –2 °C in winter and about 8 °C in summer.[145] Species diversity increases with decreasing latitude but is still lower in the subantarctic zone than in subtropical and tropical regions; however, species are often highly abundant. Compared with the terrestrial flora of Antarctica, vascular plants are diverse, with several flowering plants, including megaherbs and grasses; only two flowering plants are found on the Antarctic Peninsula. Mosses and liverworts are a significant component of the landscape.[121] Trees and shrubs are absent from the Australian subantarctic islands, but do occur on other subantarctic islands.

The faunal diversity is dominated by invertebrates and includes microarthropods, such as springtails, and insects including beetles and flies. Many vertebrates, such as flying seabirds, penguins and seals, rely on the ocean for food but depend on the islands for breeding and moulting sites.

Box 7.3 Changes in vegetation communities in Antarctica

The vegetation of East Antarctica is limited to the small areas that are ice-free for some of the year and comprises only cryptogamic organisms: lichens, bryophytes, algae and cyanobacteria. These plants are mainly influenced by three factors: the availability of water, nutrients and ultraviolet B (UVB) radiation. While lichens can obtain moisture and nutrients from the air and snow fall, bryophytes are restricted to areas of reliable water supply and occur therefore largely in the vicinity of summer melt streams (Figure A).

Antarctic soils are typically not well developed and are low in carbon and nutrients. Nutrient sources include windblown inputs from nearby penguin rookeries and past guano deposits from abandoned rookeries.[129] The growing season is restricted to the summer months when there is adequate light and water. For example, the growing season for mosses is only 1–3 months and growth rates are therefore very slow at around 1 millimetre per year.[130] The subantarctic and Antarctic Peninsula regions, which support some vascular species, have undergone considerable warming in recent decades[131] and plant communities have changed in response to this environmental shift. Until recently, the situation for continental Antarctica, and particularly East Antarctica, was unclear. However, recent studies provide evidence of significant warming.[16,38,51] Plants also have to cope with increased UVB radiation because of ozone depletion,[132-133] and increased disturbance where they occur near human habitation. There is also evidence of increased drying of plants, possibly due to increased wind speeds.

Photo by Sharon Robinson, University of Wollongong

Photo by Jane Wasley, Australian Antarctic Division

Figure A Antarctic bryophytes

Well-developed community (left). Moribund bryophytes on an undulating substrate encrusted with lichens, dominated by *Xanthoria mawsonii* (orange), *Candelariella flava* and/or *Caloplaca citrina* (yellow) and *Pseudephebe minuscula* (black) (right).

How do different species respond?

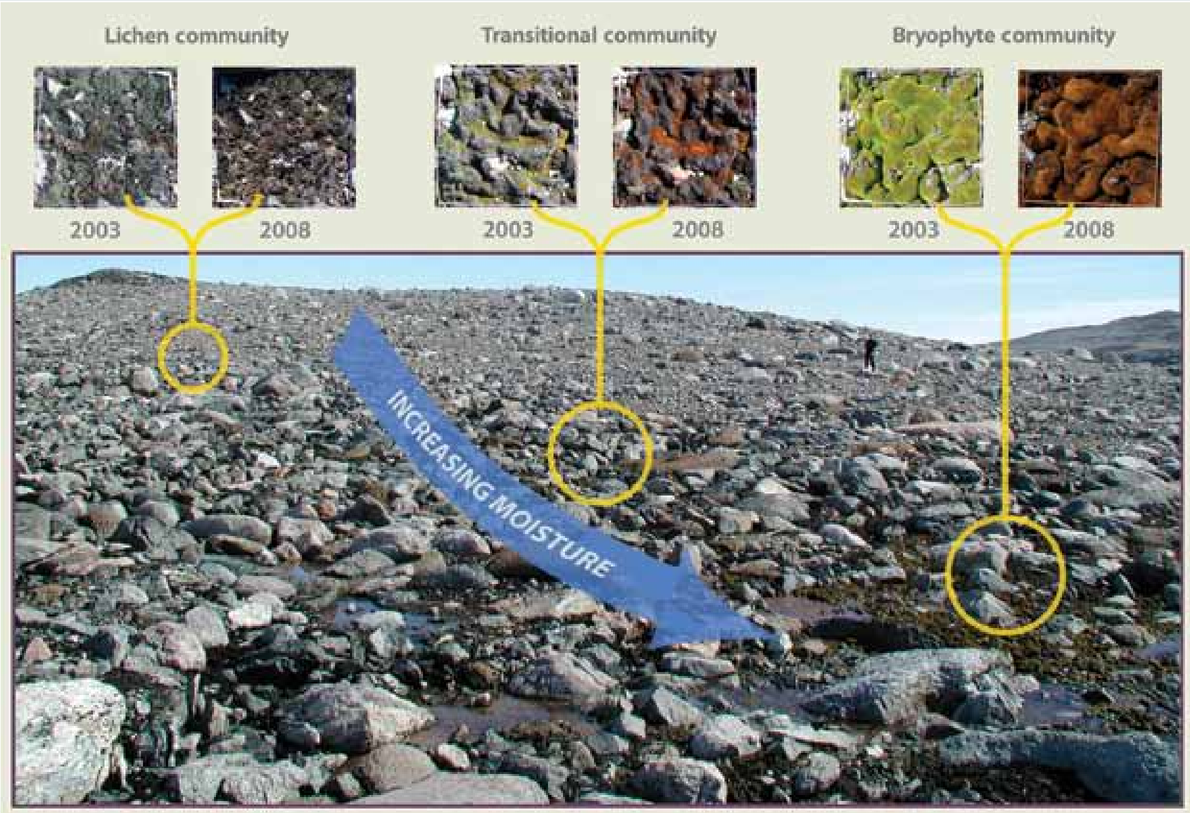
The different plants respond in varying ways to environmental stressors. Different plants form communities along a moisture gradient (Figure B). Bryophytes will be the vegetation component most at risk from changes in the water regime. The endemic species *Schistidium antarctici* (also known as *Grimmia antarctici*) is more sensitive to UVB than other species, because it lacks UVB screening pigments.[134-136] The widely distributed species *Bryum pseudotriquetrum* and *Ceratodon purpureus* both have more of these pigments and are more resilient to UVB radiation than *S. antarctici*.[137-138] *C. purpureus* is the most resilient, probably because it has cell wall–bound screening pigments that offer good protection.[134,139] *C. purpureus* and *B. pseudotriquetrum* also are more resilient to desiccation,[140-141] while *S. antarctici* is probably most tolerant of freezing conditions.[142]

What are the potential long-term consequences of pressures on communities?

The long-term consequence of a drying trend is that *S. antarctici* may be at risk, along with the invertebrate and microbial communities that it supports. Potentially, the existence of all mosses is at risk because of an increased frequency of freeze–thaw cycles and a drying environment, due to depletion of permanent snow and ice reserves, with more frequent cycles of dehydration–rehydration and a shorter growing season.

Low genetic diversity and lack of sexual reproduction mean that these organisms are probably not equipped to quickly adapt to change.[143-144] With UV levels predicted to remain high until mid-century, plus the predicted warming of the atmosphere in Antarctica, the habitat of the vegetation communities is expected to be severely compromised.

Box 7.3 *continued*



Design by Andrew Netherwood, Netherwood Design; photos by Sharon Robinson, University of Wollongong, and Jane Wasley, Australian Antarctic Division

Figure B Robinson Ridge site, showing the community gradient and comparison from 2003 and 2008

The community gradient is found along moisture gradients.

Changing environmental conditions may increase the likelihood of alien species establishing themselves in new niches in areas that are, at the moment, too extreme for them to survive.[146] Such changes could become a threat to important areas of biological, scientific, historic, aesthetic and wilderness values.

In the Australian research program, detailed studies of the subantarctic terrestrial environment and environmental change are largely limited to ongoing work at Macquarie Island. A number of vertebrate species have become established on the island. European starlings (*Sturnus vulgaris*), for example, are self-introduced via New Zealand, while European rabbits, rats and mice arrived with the sealers in the 19th century. Some of these populations, such as the rabbits, have reached vast numbers, which have significantly affected the island's terrestrial environment (Box 7.4). For example, excessive grazing by introduced rabbits destabilised the underlying rock and soil and—in conjunction with high rainfall—led to massive landslides near penguin colonies, killing large numbers of birds.[147] Since similar introductions did not occur on Heard Island or the Antarctic continent, the findings at Macquarie Island are unique to its ecosystem and cannot be extended to other areas.

Box 7.4 Degradation of the coastal vegetation by rabbit grazing

Since 2002, rabbit numbers have dramatically escalated on Macquarie Island, causing widespread vegetation damage and destruction from grazing. Many coastal slopes were transformed from lush, waist-high vegetation to grazing lawns or bare ground increasingly prone to landslips from high rainfall events and seismic activity. Seabird colonies have been affected through loss of protection afforded by vegetation, and loss of habitat and breeding grounds. Some vegetation types, such as *Polystichum vestitum* fernbrakes, are under threat[146] and remaining patches have been fenced to maintain existing populations. Populations of rats and mice have also been increasing since the cats that were introduced to the island in the early 1800s were eradicated in 2001.[146] The current Macquarie Island Pest Eradication Project aims to eradicate rabbits, rats and mice simultaneously. In 2010, the rabbit calicivirus was released on the island as part of the eradication program and has reduced rabbit numbers dramatically. In some areas, the vegetation is showing promising signs of regenerating only five months after the release of the virus. Eradication efforts are continuing.

Close-up of part of a *Polystichum vestitum* fernbrake at Finch Creek in 2001 (photo by Kate Kiefer, Australian Antarctic Division)

In 2007, the habitat at Finch Creek has been completely replaced by a new suite of herbaceous species (photo by Kate Kiefer, Australian Antarctic Division)

7.4 Assessment summary

State and trends of the terrestrial environment of Macquarie Island

Component	Summary	Assessment grade: Very poor	Poor	Good	Very good	Confidence: In grade	In trend
Coastal vegetation	Degraded through rabbit grazing						
Upland vegetation	Degraded through rapid dieback, probably climate induced						
Terrestrial invertebrate populations	Variable responses but major degradation and change from rabbit grazing						
Stream invertebrate populations	Degraded through rabbit grazing						

Recent trends

- Improving
- Deteriorating
- Stable
- Unclear

Confidence

- Adequate high-quality evidence and high level of consensus
- Limited evidence or limited consensus
- Evidence and consensus too low to make an assessment

Grades

Very good	Communities are not affected by changes and operate at maximal reproductive capacity
Good	Few communities are affected and operate below maximal reproductive capacity; structure and function of system/community not impaired
Poor	Some communities are affected and operate well below maximal reproductive capacity; structure and function of system/community impaired
Very poor	Affected systems/communities barely functional

2.3.3 Vertebrate populations

Antarctic vertebrates encompass a variety of flying seabirds and penguin species, several seal and whale species and numerous fish species. The species diversity, especially on the Antarctic continent, is greatly reduced compared with the temperate and tropical regions and even the Arctic. However, the abundance of many species is very high. All are highly dependent upon the Southern Ocean for food, while their breeding areas include terrestrial, fast ice and marine regions. Many of the large, air-breathing vertebrates are also highly migratory and explore areas far outside the Antarctic and the Southern Ocean.

Status and trend data are available for only a few species, notably the two penguin species on the continent, some albatross and giant petrel populations, and fur and elephant seals at Macquarie Island. Long-term population data do not exist for the ice-breeding seals and whales, most of the flying birds and some of the penguins at Macquarie Island. Hence, trends and status are difficult to establish. Heard Island and McDonald Islands are visited infrequently and data are largely lacking.

Fish

The fish fauna of Antarctica is unique. Their species composition and to a large extent their distribution in the Southern Ocean have been well documented. There are some 322 recognised species in Antarctic waters but only about half (161 species) live in the high Antarctic (i.e. south of the Antarctic Polar Frontal Zone).[26] Of those, most (77%) are notothenioids—the most diverse group, with 129 species belonging to five families.[148] Their biomass makes up 91% of the Antarctic fish fauna.[26] Notothenioids have lived in the Antarctic environment for millions of years and are well adapted to life in a polar ocean. Key to their survival in the freezing temperatures is that these fish evolved to produce glycoproteins that act as antifreeze agents in their blood.[149]

In terms of their populations, there is virtually no information on the status and trends of Antarctic fish. This is partly due to the vast area covered by the Southern Ocean that renders population surveys near impossible, especially those frequent enough to estimate abundance and trends. Therefore, formal stock assessments are only available for some of the exploited fish populations.

Historically, vessels from the Soviet Union and other Eastern Bloc countries conducted large-scale fishing operations in the Southern Ocean off the AAT in the mid-1960s. Marbled rock cod (*Notothenia rossii*) was caught in such quantities that the stock had noticeably reduced by the 1970s and was depleted by the end of the 1980s to a point at which commercial operations were no longer profitable. Off South Georgia, stocks had all but disappeared after only two years of fishing.[150] Currently, only two species of finfish are harvested in the Australian exclusive economic zone at Heard Island and McDonald Islands, and Macquarie Island: the Patagonian toothfish (*Dissostichus eleginoides*) and the mackerel icefish (*Champsocephalus gunnari*). The latter is being targeted only at Heard Island and McDonald Islands.

CCAMLR regulates all legal commercial catches, but illegal, unregulated and unreported fishing still occurs in the high seas of the CCAMLR area, albeit at probably lower levels than in the 1980s and 1990s. It is worth noting that in 2010, no illegal, unregulated and unreported fishing was reported in Australia's exclusive economic zone at Heard Island and McDonald Islands, or at Macquarie Island.

Whales

Both toothed and baleen whales are found in Antarctic waters, at least during the southern summer. The former comprise several species, some of them rare, and include killer whales or orcas (*Orcinus orca*) and sperm whales (*Physeter macrocephalus*). Baleen whales include the blue (*Balaenoptera musculus*), Antarctic minke (*B. bonaerensis*), fin (*B. physalus*), sei (*B. borealis*), humpback (*Megaptera novaeangliae*) and southern right (*Eubalaena australis*) whales. Most Antarctic baleen whale species spend the summer in the open waters of the Southern Ocean, where they feed extensively as the sea ice recedes. In autumn, they migrate north to warmer waters where they give birth to their young.

By the mid-1900s, a number of great whale species (e.g. blue, humpback and sei whales) living in the Southern Ocean had nearly become extinct after decades of intensive hunting.[151] Today, despite efforts to protect them by banning commercial whaling and declaring the Southern Ocean an international whale sanctuary, rates of recovery vary among species and regions, and some populations are still showing no sign of recovery.[152] The reasons for this are largely unknown. Blue, fin and sei whales are listed by the International Union for Conservation of Nature as endangered species, while sperm whales are classified as vulnerable to extinction. Blue whales have not been hunted for 65 years, but so far there are only very limited indications of a possible population recovery.[153] On the other hand, humpback and southern right whales are comparatively abundant again and are listed as being of least concern. However, the vast abundance of whales from pre-industrial times will, in all likelihood, remain a thing of the past.[154]

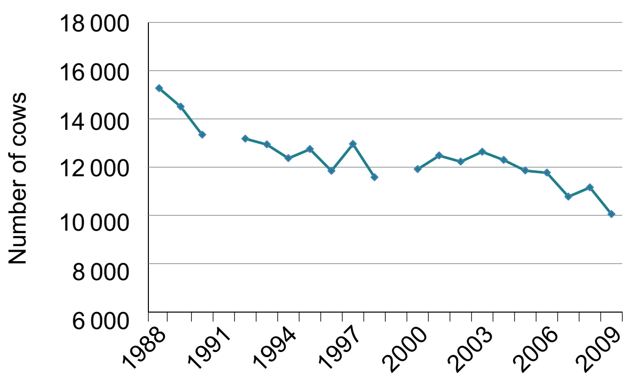
Seals

Four species of seal (crabeater, leopard [*Hydrurga leptonyx*], Ross [*Ommatophoca rossii*] and Weddell [*Leptonychotes weddellii*]) inhabit the sea ice zone that surrounds Antarctica and are reliant on the sea ice at critical stages of their lives, particularly in the reproductive and moulting periods. Their populations are difficult to study because these seals are highly mobile, are dispersed over very large and inaccessible regions, spend long periods of time foraging in the ocean where they are difficult to survey, and do not appear to occupy set territories. Sightings are usually of individuals or very small groups. Surveys to estimate their population sizes are infrequent because they are expensive and labour intensive. Consequently, population trends are largely unavailable.

In the past, estimates of the global population of crabeater seals ranged from 2–5 million individuals in the mid-1950s[155] to about 75 million in the early 1970s[156] and 11–12 million in the 1990s.[157] In 1972–73, Laws estimated 772 000 crabeater seals in the Wilkes Land region, East Antarctica,[7] and postulated that these seals should increase in numbers because of all the 'excess' krill available after many krill-eating whales had been removed from the Southern Ocean. A detailed aerial survey of 1.5 million square kilometres from 64°E to 150°E, roughly coinciding with the area where Laws operated, was conducted in 1999–2000. If Laws' krill surplus hypothesis had been correct, several million crabeater seals could have been expected. However, the survey estimate for crabeater seals yielded fewer than 1 million individuals in the survey area with a range of 0.7–1.4 million.[158] Thus, it appears that crabeater seals are abundant but that earlier estimates were too high. Leopard and Ross seals are probably also abundant, but less so than crabeater seals, with numbers in the tens of thousands.[159-160]

Crabeater, leopard and Ross seals inhabit the northern region of the sea ice that consists of ice floes of varying sizes and density—known as pack ice. Weddell seals are found on the fast ice—the sea ice that is attached to the continent. How the pack ice seals respond to environmental stressors may vary among species.[161] However, changes in the structure and size of ice floes could lead to the loss of pupping platforms. A reduction in sea ice persistence may decrease the availability of Antarctic krill, an important food source for all pack ice seals—although, if coastal polynyas (ice-free areas) increase in size, crystal krill may become more abundant and may partially offset the loss of Antarctic krill.[162] Leopard seals have the most diverse diet among the ice seals and are likely to be least immediately affected by changes in food availability. However, depending on the rate, kind and magnitude of change, they are likely to be affected eventually.

Antarctic fur seals (*Arctocephalus gazella*) and southern elephant seals (*Mirounga leonina*) inhabit the subantarctic islands, but can be encountered as far south as the Antarctic continent. While fur seal populations appear still to be increasing, the numbers of southern elephant seals at Macquarie Island are still in decline (Figure 7.7). The reasons for this are unknown and difficult to investigate, because this species performs long-distance migrations for 8–10 months each year;[163] however, elephant seals are probably subjected to a number of different pressures throughout the year, as well as at various stages of their lifecycle.



Source: Gales & Burton[164]

Figure 7.7 Number of southern elephant seal cows at Macquarie Island (counted each year on 15–16 October), 1988–2009

Flying seabirds

Seabirds are typically long lived. They mature late and only lay one or two eggs per year, which are not usually replaced if lost. Also, some albatross species breed only every second or sometimes third year. Although adult survival is usually very high (around 95% of adults return the following year to their colonies), their low reproductive output does not enable seabirds to withstand even small increases above their natural mortality rates.

Most seabird populations in the Antarctic are only infrequently surveyed, because it is difficult to access their colonies. Consequently, few seabird populations have been assessed in a reliable way. Populations comprising fewer than 100 breeding pairs are extremely vulnerable. About one-third of global albatross populations are in this category, including most breeding populations at Australia's subantarctic islands.

The threats that seabirds encounter at sea include competition with commercial fishers for their prey species, death or injury as bycatch in longline and trawl fisheries, intentional shooting, increased dependence on fisheries' discards, and injury from marine pollution. The consequences of global warming and ocean acidification are also likely to threaten many seabirds by affecting the abundance and spatial distribution of their food supply.

On land, seabirds may experience disturbance by humans, loss of breeding habitat, and—because of increased competition for nest sites—exposure to parasites and pathogens. On subantarctic islands, their breeding success can be reduced directly by alien predators, such as cats, rats and mice, as happened on Macquarie Island. Heard Island has so far remained free of introduced vertebrates. Alien species can also have an indirect effect where overgrazing leads to destabilisation of the substratum, which in turn can lead to an increase in landslides.[165]

One of the most serious threats to seabirds, particularly those breeding at lower latitudes on the subantarctic islands, is commercial fishing operations. Within the Australian jurisdiction, incidental seabird mortality is strictly controlled and regulated. However, seabirds fly enormous distances and often forage in the high seas in international waters where they interact with the pelagic longline fisheries. The seabirds become hooked when they scavenge for food behind the vessels; as the line sinks, they drown. Significant research has been undertaken and mitigation methods adopted by CCAMLR as a result have seen the seabird mortality reduced to near zero in the legal fishery. The approach taken is to collaborate with industry members to develop gear that is seabird-safe but does not impact on catch rates of fish (see Box 7.8). CCAMLR continues to monitor fishery interactions with seabirds and has been adjusting the mitigation methods accordingly.

Penguins

In terms of biomass, most Antarctic seabirds are penguins—they make up about 90% of the total avian biomass.[120] Like all seabirds, penguins are long lived and only produce one or two eggs per year. Penguins often live in large colonies in the coastal areas of subantarctic and Antarctic islands. During the breeding season, the foraging areas of the breeding population are limited, because they need to return regularly to their colonies to feed their offspring. Of the 18 species in the penguin family, 7 live and breed in the AAT at Macquarie Island, but only emperor penguins (*Aptenodytes forsteri*) and Adélie penguins inhabit colonies in the high Antarctic. Adélie penguins spend the winter months at sea, returning to their breeding colonies during the southern summer, while emperor penguins breed during the winter months and fledge their young in summer. Consequently, these two species are subject to marine and terrestrial processes at different times of the year.

Penguins moult once a year. To prepare for the moult, they feed extensively to lay down sufficient reserves of body fat; during the moult, they cannot fish as their plumage is no longer waterproof. Thus, for several weeks they survive on stored body reserves. With the exception of gentoo penguins (*Pygoscelis papua*), they forage offshore and are migratory outside the breeding season.[166]

The greatest threats for penguins in East Antarctica are likely to be loss of breeding habitat (in the case of emperor penguins) and a reduction in food availability due to global warming and ocean acidification. Changes in sea ice conditions have varied consequences (Box 7.5). For example, a reduction in the sea ice extent potentially shortens foraging distances, but less sea ice also means a reduced production of krill.[167] It is difficult to predict to what extent penguins may be able to adapt to environmental change, particularly as the rate of change is likely to increase once the ozone loss is reversed, making adaptation difficult for these long-lived species.

Box 7.5 Sea ice and breeding success of Adélie penguins

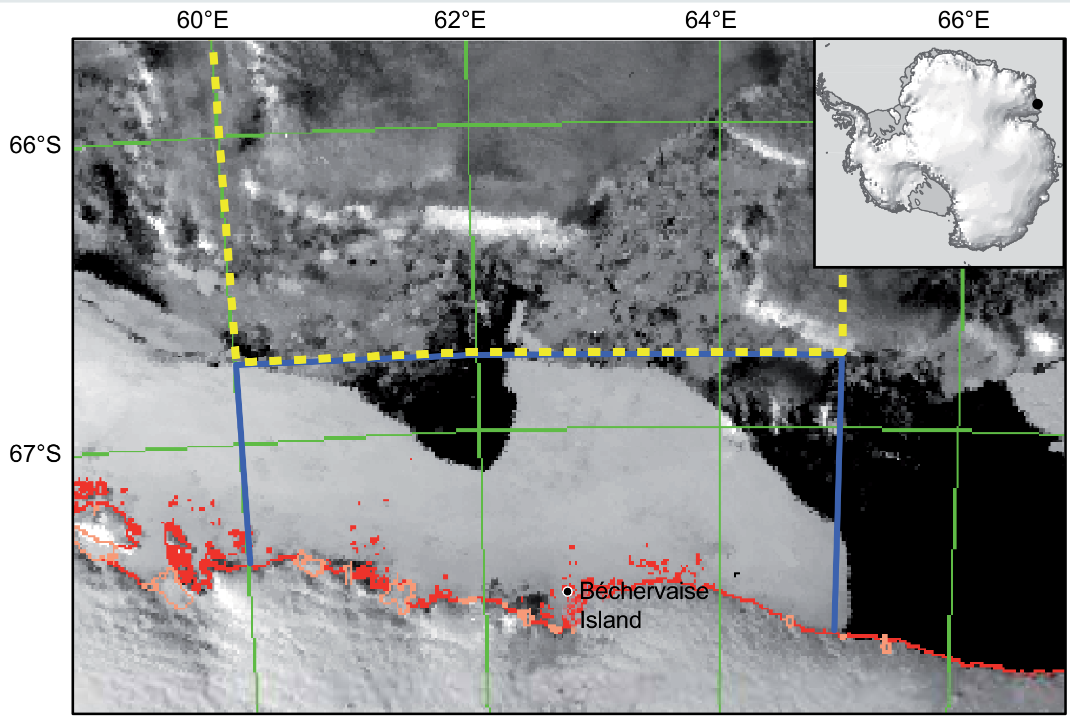
Adélie penguins breed in colonies that are distributed all around the Antarctic continent. They breed in summer and usually lay two eggs. A number of studies investigated the complex link between the breeding success of Adélie penguins and the extent of sea ice, as well as the length of time it persists (e.g. Emmerson & Southwell[168]). Sea ice exists in two main forms:

- the continuous sheet of land-fast ice that largely excludes the penguins from potential foraging areas
- the pack ice north of the fast ice that, because it is subject to wind and wave action, consists of mobile ice floes that allow penguins to access the sea.

The breeding success of Adélie penguins depends upon the food available to them during winter, and their body condition at the beginning of the season (they have to have sufficient body reserves to start breeding). It may also depend on the distance they have to travel across the fast ice to their colonies (Figure A).

A 17-year study at Béchervaise Island, off Mawson Station, showed Adélie penguins bred most successfully in years when the winter sea ice was extensive (producing a lot of food and enabling the penguins to build up their body reserves), and when the nearshore fast ice was reduced during the breeding season, allowing the penguins quick access to foraging areas and ensuring a good food supply for chicks. In addition, during successful years, the offshore sea ice was still extensive and provided reliable food production, access and a platform for resting and predator avoidance for the penguins.[168]

Thus, the timing, quality and extent of both fast and pack ice contribute to the breeding success of Adélie penguins. To predict how Adélie penguin and other top predator populations are affected by changing environmental conditions, it is necessary to determine which factors ultimately influence their reproductive success and long-term survival. The extent of the fast ice is certainly an important factor.[168] In years when the fast ice persists throughout the summer, Adélie penguins suffer a significant reduction in breeding success, and even complete breeding failure.[169]



Source: Emmerson & Southwell,[168] courtesy of the Ecological Society of America, © Ecological Society of America

Figure A Satellite image of the Mawson region in East Antarctica taken on 2 January 1995

The area of ice cover was calculated between 60.8°E and 65.8°E for nearshore fast ice (solid blue line), extending from the coastline out to 66.8°S; offshore pack ice (dashed yellow line), extending northward of 66.8°S; and total ice cover (sum of nearshore and offshore) from the coastline northward. The coastline is in red, and the boundaries of ice tongues and shelves are in pink.

7.5 Assessment summary

State and trends of Antarctic and subantarctic vertebrates

Component	Summary	Assessment grade (Very poor / Poor / Good / Very good)	Confidence: In grade	Confidence: In trend
Fish	Geographic distribution and species composition of Antarctic fish reasonably well understood; however, abundance estimates or population size estimates are not available			
Toothed whales	Whales found in Antarctic waters include sperm whale and orcas; many species are data-deficient and their populations and trends cannot be estimated			
Baleen whales	Includes the Antarctic blue, sei, fin, minke and humpback whales; all but minke whale species are listed by the IUCN on the Red List of Threatened Species			
Ice-breeding seals	Populations apparently abundant and unaffected by human activities; however, much is still unknown and population trend data are not available			
Fur seals	Populations still recovering from sealing exploitation, but are increasing			
Elephant seals	Population at Macquarie Island still decreasing; reasons are unknown			
Wandering albatrosses	Listed as vulnerable; only about 10 breeding pairs at Macquarie Island; commercial fishing operations are a threat			
Small albatrosses	All species are listed by the IUCN because of conservation concerns; many are caught as bycatch in commercial fisheries			

Component	Summary	Assessment grade (Very poor / Poor / Good / Very good)	Confidence: In grade	Confidence: In trend
Antarctic petrels	Long-term population data for these birds not available; however, they still appear to be abundant	?	◒	○
Subantarctic petrels	Long-term population data not available for most species; however, some populations are known to have decreased (e.g. at Macquarie Island)	?	◒	○
Antarctic penguins	Overall, penguin populations appear to be stable in the Australian Antarctic Territory; however, long-term monitoring studies are limited to a small number of sites Populations breeding in other areas of Antarctica are showing rapid declines coinciding with decreases in sea ice	—	◒	◒
Subantarctic penguins	Many species appear to suffer population declines, but long-term population data are available only for a few colonies King penguins appear to be the only species with a growing population	↙	◒	◒

Recent trends
- ↗ Improving
- ↙ Deteriorating
- — Stable
- ? Unclear

Confidence
- ● Adequate high-quality evidence and high level of consensus
- ◒ Limited evidence or limited consensus
- ○ Evidence and consensus too low to make an assessment

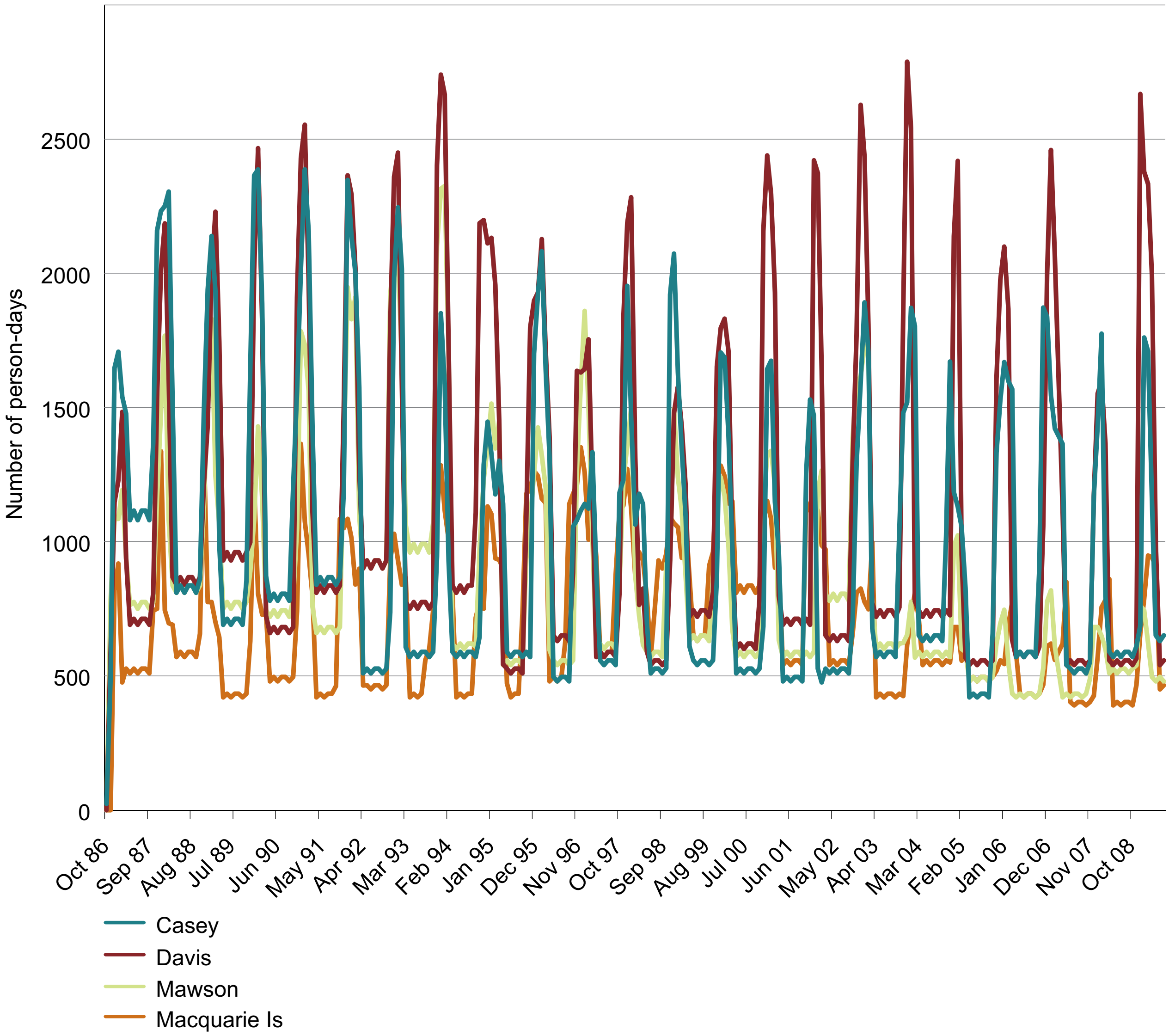
Grades
- Very good: Only a few, if any, species or species groups have declined as a result of human activities or declining environmental condition
- Good: Populations of a number of species or species groups have declined significantly as a result of human activities or declining environmental condition
- Poor: Populations of many species or species groups have declined significantly as a result of human activities or declining environmental condition
- Very poor: Populations of large numbers of species or species groups have declined significantly as a result of human activities or declining environmental condition

IUCN = International Union for Conservation of Nature

2.4 The station environment

Human activities in Antarctica are very limited in comparison to other continents. There are no permanent populations living in Antarctica and neither industrial nor agricultural activities occur there. However, although the human presence is quite small compared with the overall size of the continent, human activities are concentrated on small ice-free areas adjacent to the coast, because they are easy to access by ship and they provide a stable surface for building. These ice-free areas are also home for most of the land-living plants and animals of Antarctica. The environmental impacts of human activities are concentrated in these areas, and impacts include disturbance to the landscape and contamination with pollutants.

Australia operates three permanently occupied research stations on the Antarctic continent (Casey, Davis and Mawson), as well as a station at Macquarie Island, and uses various ships and aircraft to transport people and goods to and from the stations.



Source: Ayton[170]

Figure 7.8 Number of person-days by month for all Australian Antarctic stations, 1986–2009

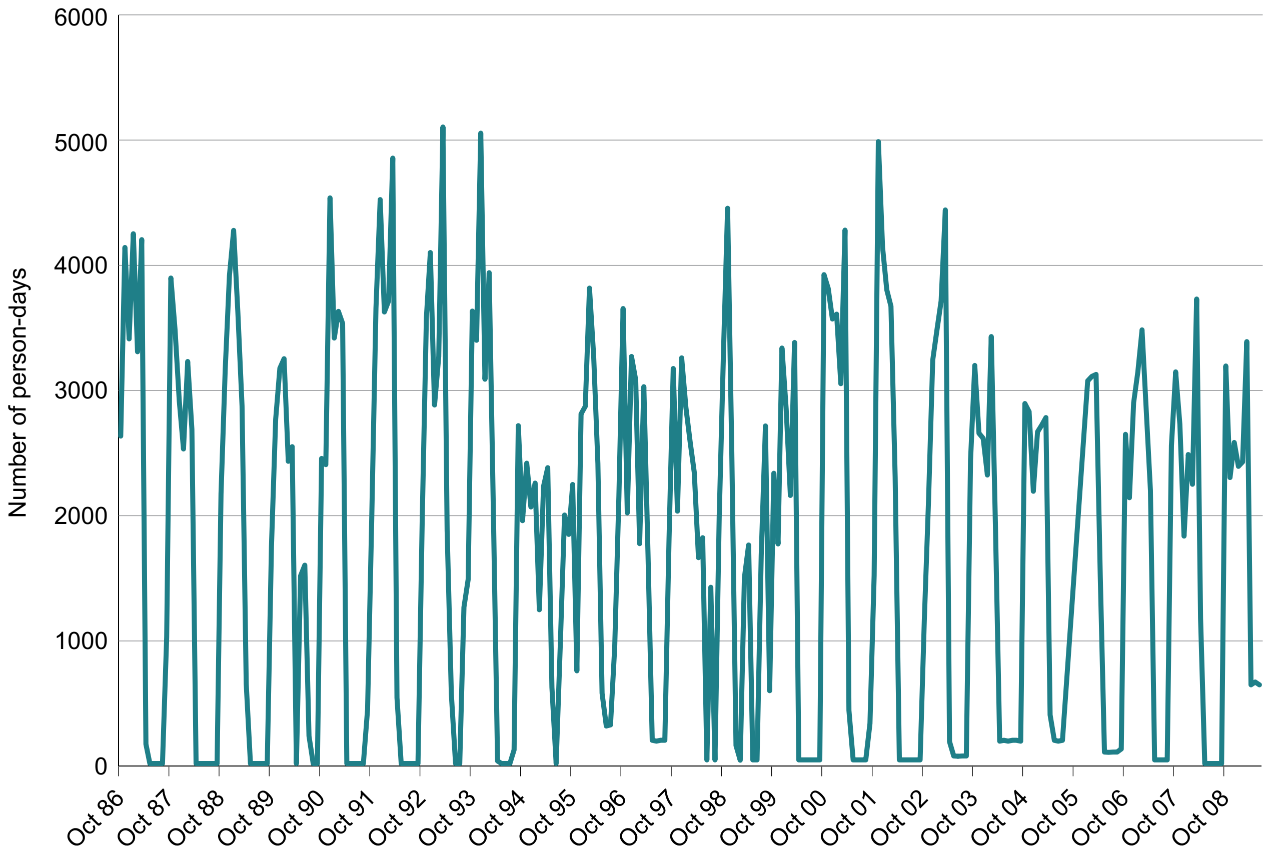
2.4.1 Operational indicators

Under Article 17 of the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol), all parties are required to provide an annual report on steps taken to implement the protocol. To help monitor and manage the ways in which the Australian Antarctic program interacts with the Antarctic environment, the Australian Antarctic Division established a set of operational indicators. A number of these are discussed below. Annex III to the protocol outlines minimum requirements for waste disposal and waste management practices in the Antarctic, and this forms the basis of the division's waste management practices.

The operational indicators provide information about the actual or potential impacts of Australian Antarctic program operations on the Antarctic environment. The number of people present at or near the stations and on the ships is recorded monthly and reported annually (Figures 7.8 and 7.9). This provides a measure of the human pressure on the natural environment. Population sizes vary among the stations, between seasons (summer versus winter) and with year, depending on the research and building and maintenance requirements.

In the most recent decade, the winter populations on stations ranged from 14 at Macquarie Island to 25 at Davis Station. Since the rodent and rabbit eradication program began in 2010, the winter population has more than doubled at Macquarie Island. In 2011, there are 40 personnel on the island. Davis Station, where a variety of research, maintenance and building programs occur, has had the largest population over summer for many years, of up to 100 personnel.

The Australian Antarctic Division operates ships only from mid-October until April the following



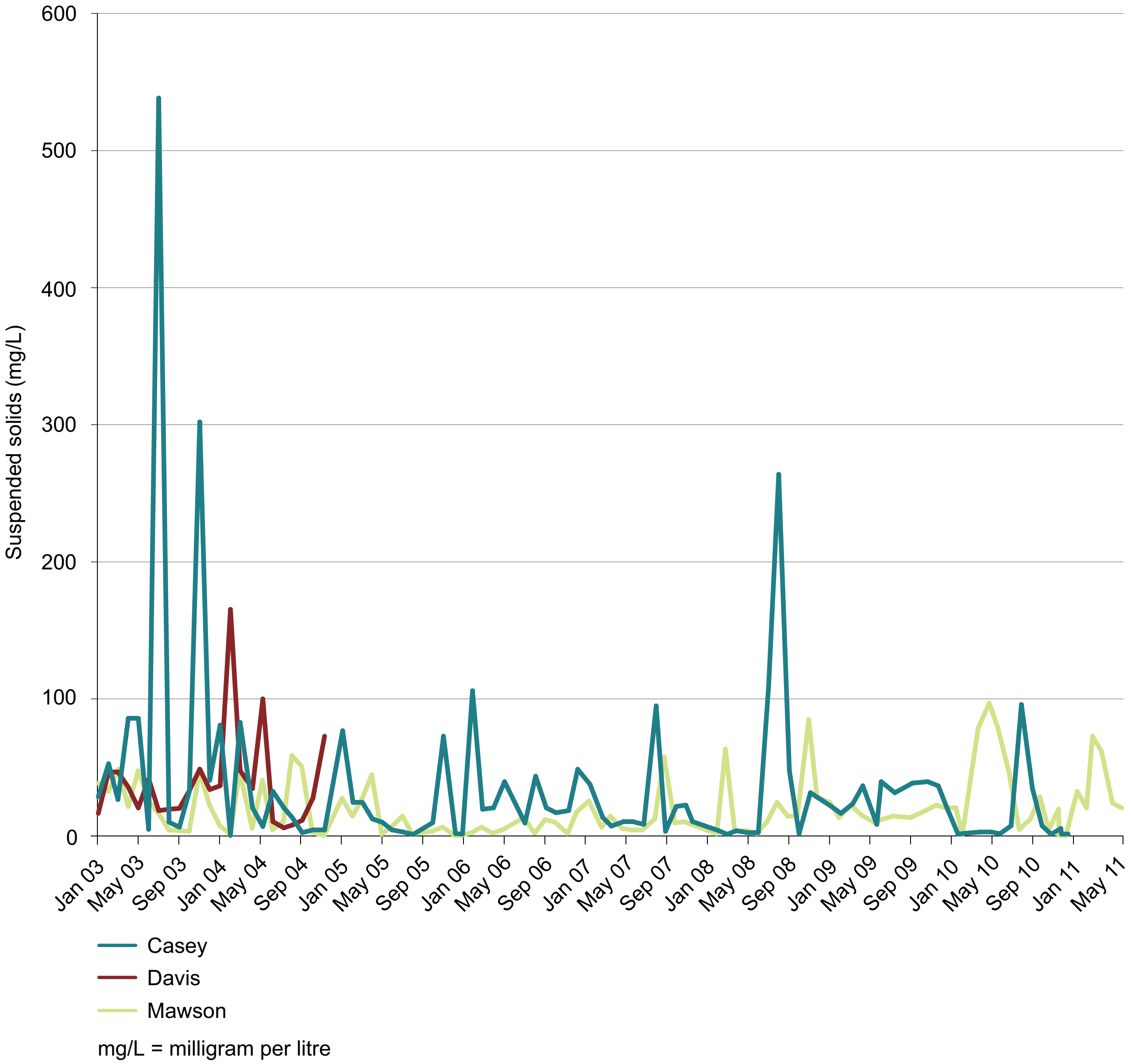
Source: Ayton[170]

Figure 7.9 Number of person-days by month for all ships operated by the Australian Antarctic Division year. Winter travel by ship is impossible because of the extensive sea ice. Voyages have different purposes, such as deployment and retrieval of personnel, resupply of stations and marine science research. The ice breaker RSV *Aurora Australis* caters for all these purposes. However, supplying four stations in a timely manner with one vessel has proven to be a challenge. Hence, personnel may be deployed, for example, via tourist vessels that visit Macquarie Island. Occasionally, vessels larger than the *Aurora Australis* are chartered for a particular task, such as removal of waste (Box 7.7, p. 520).

Waste treatment and disposal

Waste treatment and disposal are a measure of human impact. The stations produce liquid waste comprising human waste, waste from kitchens and bathrooms, and limited volumes from workshops. Contamination of the latter is usually minimal as it is cleaned of oil before discharge into the sewage system. Wastewater effluent is discharged directly to the sea adjacent to the stations.

At Davis Station and Macquarie Island, sewage is macerated and released. Maceration is the minimum



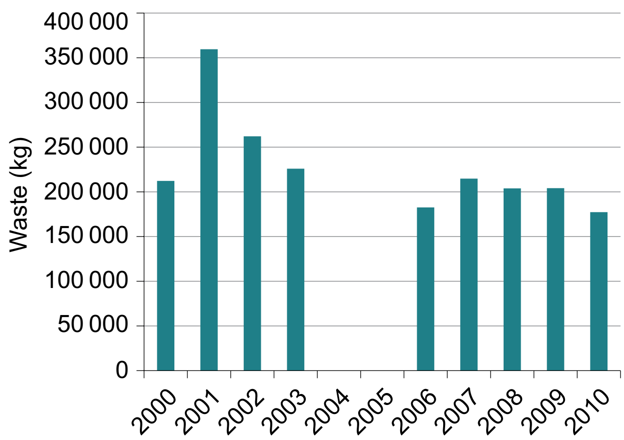
Source: Ayton & Price[171]

Figure 7.10 Amount of suspended solids in the effluent of Australia's three Antarctic stations, 2003–11 level of sewage treatment required under the Madrid Protocol. At Macquarie Island, sewage is discharged into a high-energy environment where the macerated particles are quickly diluted and dispersed. The wastewater treatment plant at Davis ceased to function and was removed in 2005. In the summers of 2009–10 and 2010–11, the Australian Antarctic Division investigated the potential impacts of sewage on the marine flora and fauna. Once available, the results of this research will inform decisions about future waste treatment options.

At Casey and Mawson stations, treatment plants process the sewage before it is released into the ocean. One of the measures used to assess waste treatment is the 'biological oxygen demand', which indicates how efficiently the stations' waste treatment plants remove organic matter from the sewage and how much organic matter is being released into the ocean. The quantities of suspended solids are also measured. Suspended solids indicate how efficiently the waste treatment plants break down organic matter, as well as the amount of organic matter that is released into the ocean as a result of human occupation (Figure 7.10).

In 1991, the parties to the Antarctic Treaty introduced the Madrid Protocol. Waste is minimised wherever possible; for example, by reducing packaging—goods delivered to Antarctica are contained in minimal packing, and substances such as washing powders and dishwashing liquids are biodegradable. Most rubbish and material no longer required are collected and returned to Australia (Figure 7.11) where they are reused, recycled or disposed of. Waste typically includes battery acid, laboratory chemicals, sewage sludge, paint, oil, paper, glass, aluminium, plastic (PET and HDPE), steel, copper, brass and building materials. Some waste, such as kitchen scraps and soiled food wrappers, is incinerated, resulting in exhaust emissions to the environment. For example, burns containing plastics generate hydrogen chloride; toxic gases, such as toluene, sulfur dioxide and chlorobenzene can also be generated. The ash may contain heavy metals.[172] Australia aims to reduce the amount of materials incinerated on the stations, either by reducing the amounts of certain materials sent to the stations, or by diverting materials from incineration to reuse or recycling. Ash from the incinerators is returned to Australia. Data collected on waste levels enable the evaluation of the environmental impacts of operational and scientific activities, and the extent of community adoption and the economics of recycling.

Waste is returned by ship usually during the stations' resupply. How much waste is returned to Australia each year is highly variable and dependent upon the availability of cargo space on the ship. When necessary, vessels are hired especially for the purpose of returning waste; for example, in 2010–11 for the clean-up of the tip site in the Thala Valley (Box 7.7, p. 520).



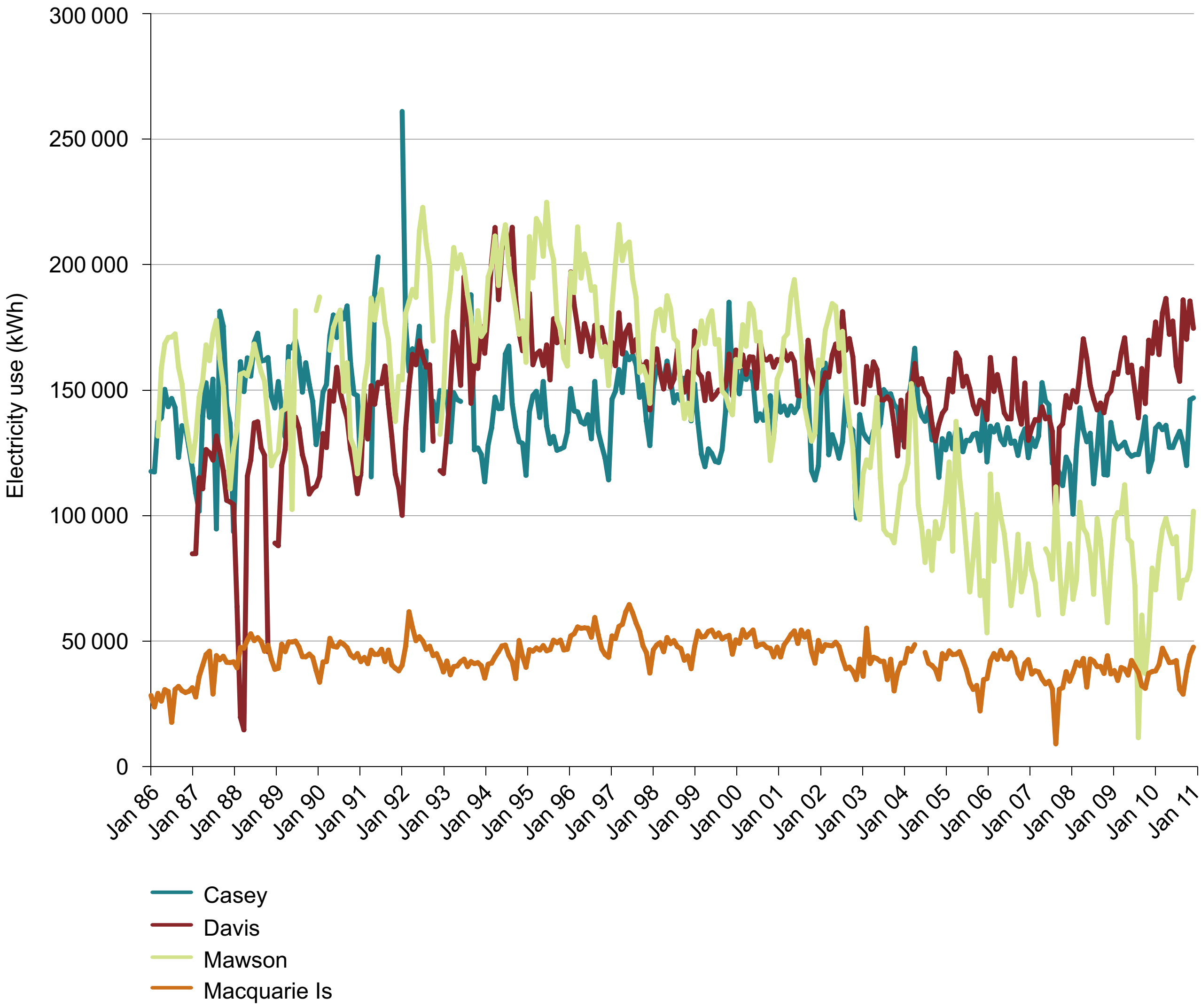
kg = kilogram
Source: Frost[173]

Figure 7.11 Amount of total waste returned from the three Antarctic stations, and Macquarie Island, 2000–10

Fuel usage

The quantity of fuel used by generator sets and boilers at all stations is recorded because the environmental impact of the emissions released from power generation and heating is proportional to the amount of fuel used in Antarctica. Special Antarctic blend (SAB), a light diesel fuel blended especially for cold climates, is used at the stations to power the stations' generator sets, to provide heat through boilers, and to run plant and equipment including the station incinerators and vehicles.

The quantity of fuel used to generate heat and electricity is a reflection of the efficiency of various electrical and heating systems and is also affected by energy saving strategies, the number of people on the station and the amount of heat and lighting required, which varies with ambient temperature and daylight hours. The need for electricity increases from summer to winter, although fewer people occupy the stations (Figure 7.12), because current station designs mean that buildings are unable to be closed down during winter, even though some may be little used. A range of initiatives have been introduced to reduce fuel consumption wherever possible. The living areas are kept at 19 °C during the day and 16 °C at night. Those buildings that are connected to the general site services are kept warm using heat created by the generators in the powerhouse and only a few small buildings have their own electrical heating systems. Fuel-efficient 'cold pump' technology is being used for the long-term storage of perishable food. At Davis Station, air-to-air heat exchangers are used to pre-warm fresh air brought into buildings without introducing cold. At Mawson Station, two wind turbines were installed in 2003 to generate electricity (Box 7.6) and a 'smart grid' is being installed to regulate power use.



kWh = kilowatt hour

Source: Bonnice et al.[174]

Figure 7.12 Monthly electricity use at Australian Antarctic stations, 1986–2010

Box 7.6 Renewable energy production at Mawson Station

Australia's stations provide a safe and comfortable environment for the personnel living and working there. However, it costs a lot of fuel to run these stations. Electricity is required for heating and power is needed for water production, light and other necessary domestic activities. Mawson Station burns 2.1 megalitres of diesel each year, producing about 5500 tonnes of carbon dioxide.

To address this environmental impact, the Australian Antarctic Division installed two wind turbines in the summer of 2002–03. With an average wind speed of about 40 kilometres per hour, Mawson Station is Australia's windiest Antarctic station and an ideal location for the use of wind turbines. The turbines could be purchased off the shelf and required only minimal modifications to operate in the Antarctic environment. The turbines generate electricity in wind speeds ranging from 9–100 kilometres per hour and together can produce 600 kilowatts of energy.

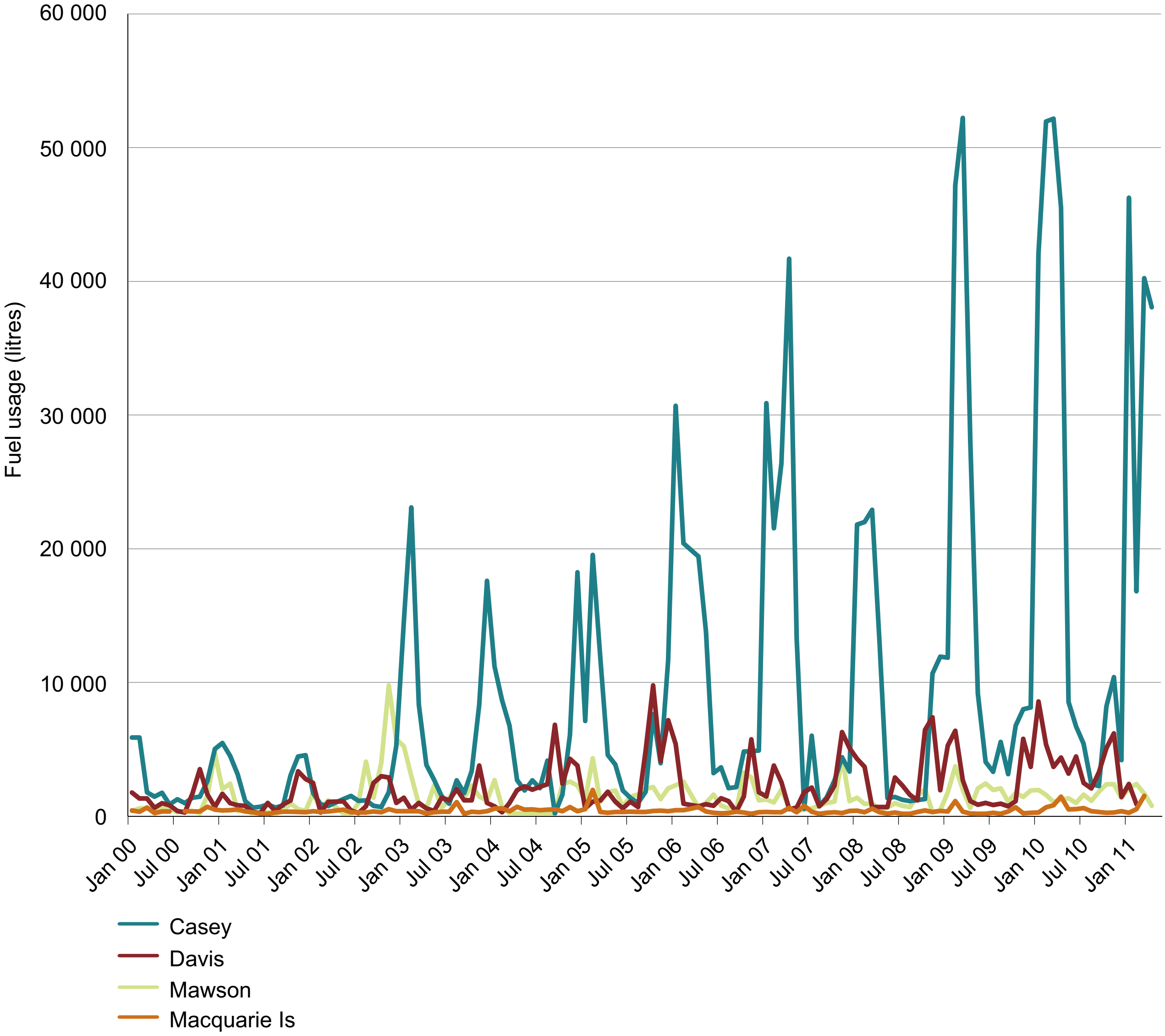
Three years after the installation, an annual fuel saving of 29% was achieved, significantly reducing the overall quantity of fuel required by the station, as well as the amount of carbon dioxide emitted. Improvements to the software through which the turbines are operated have further increased the savings. In May 2011, the turbines produced 111 495 kilowatt hours; this is equivalent to a fuel saving of 13 379 litres of diesel and 35 tonnes of carbon dioxide.

Smaller wind generators have been used successfully at field stations. The advantages of using renewable energy sources include a significant reduction in environmental and operating costs, as well as more efficient running of station operations as certain processes are now automated.

Mawson Station with wind turbine (photo by Glenn Jacobson, Australian Antarctic Division, © Commonwealth of Australia)

Fuel use by vehicles is also measured and reported. There are differences in vehicle use in summer and winter (Figure 7.13). During winter, vehicle use tends to be less than in summer—populations at the stations decrease to about 20 people or fewer and vehicles are generally not used in inclement weather. In summer, the station populations increase dramatically and with it maintenance, building and scientific activities. Since the introduction of the airlink, the fuel use at Casey Station has soared in summer and far exceeds fuel consumption at the other stations. Vehicles are required to prepare the ice runway and also to transport people between Wilkins runway (on the plateau behind Casey Station) and Casey Station. During winter, the fuel use at Casey Station is similar to that at the other continental stations. At Macquarie Island, vehicle use is largely limited to the station surroundings on the isthmus.

The quantity of fuel used by ships travelling to Australian Antarctic stations and on marine science voyages differs with variation in shipping demands between years. Marine gas oil (MGO) is a marine version of normal diesel and is used on the vessels to power the main engines and generator sets, to provide propulsion and general services to the

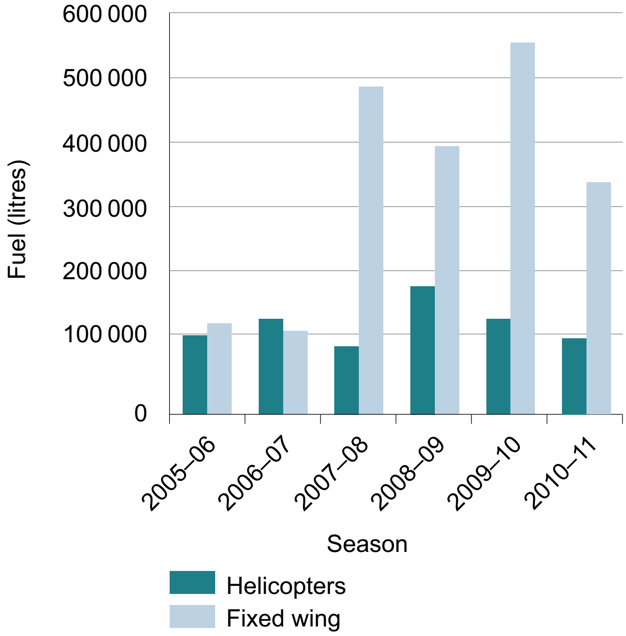


Source: Ratcliffe et al.[175]

Figure 7.13 Fuel consumption by vehicles on Australia's Antarctic stations, 2000–11 vessels, such as power and heating. IFO 40 (RMC 10) is a light-grade fuel oil used by some of the Australian Antarctic Division vessels. This fuel is used for the main engines, and in some cases the generators.

Aircraft operations

In September 2005, the Australian Antarctic Airlink between Hobart and Casey Station was launched. The maintenance of the Wilkins Aerodrome requires about 10 000 litres of SAB per week (Figure 7.14). The Australian Antarctic Division uses an Airbus A319-115LR for transport between Australia and Antarctica. This airbus was selected in part because it has sufficient range for a return trip from Hobart to Antarctica without refueling in Antarctica. This avoids a range of potential environmental risks associated with the transport, handling and storage of large volumes of jet fuel. Two smaller, ski-equipped CASA 212-400s are used for intracontinental activities in summer. Each summer, there are also two to three single-engine Eurocopter AS-350 helicopters. When required, long-range helicopters (e.g. the Sikorsky S-76) join the fleet to support a variety of biological, glaciological, geological and operational programs. The helicopters also link Davis Station and the Davis Plateau ice airstrip some 20 nautical miles from the station, where the fixed-wing aircraft land when the sea ice runway no longer exists, and provide helicopter services from the icebreaker *Aurora Australis*.



Source: Adrian Pate, Australian Antarctic Division, unpublished data

Figure 7.14 Fuel consumption of fixed-wing aircraft and helicopters operating in the Australian Antarctic program, 2005–06 to 2010–11

Data do not include ground-support fuel consumption.

Australia's icebreaker RSV *Aurora Australis* cuts through sea ice, Antarctica

Photo by Doug Thost

7.6 Assessment summary

State and trends of the station environment

Component	Summary	Assessment grade: Very poor	Poor	Good	Very good	Confidence: In grade	In trend
Person-days on ships and stations	Person-days are a proxy measure for wide-ranging human activities that can interfere with physical, chemical and biological systems. Person-days vary annually depending on the number of scientific and operational projects that are approved						
Biological oxygen demand	Estimate of the biological oxygen demand of effluent discharged into the ocean from the waste treatment plants at each continental station Impact of sewage on environment at Davis Station currently under investigation						
Suspended solids	Amount of organic matter in effluent discharged into the ocean from the waste-treatment plants at each continental station						
Waste returned to Australia	Composition and weight of waste returned to Australia from Macquarie Island and the continental stations. The amount of waste returned to Australia is dependent upon the cargo limit of the ship and varies between years						
Incinerated waste	Total weight of material incinerated, and the weights of the major components at all stations, is decreasing as importation of packing materials, for example, is being reduced						
Fuel use by generators and boilers	Quantity of fuel used by generator sets and boilers at all stations						
Fuel use by vehicles	Quantity of fuel used for vehicles at all stations is highly variable and depends on the use of vehicles; however, the total quantity of fuel across all stations is increasing						

Component	Summary	Assessment grade (Very poor, Poor, Good, Very good)	Confidence (In grade, In trend)
Electricity	Quantity of electricity used; also indicates fuel use At Mawson Station and Macquarie Island, great savings are being achieved through the use of renewable energy sources		
Fuel use by ships	Fuel use of all vessels engaged in transport of goods and people, as well as marine science voyages, varies with year because of differing demands and also variations in sea ice conditions. More fuel is required in years of heavy sea ice		
Fuel use by aircraft	Although fuel use by fixed-wing aircraft has been highly variable in the past, it has been fairly stable for the past 3–4 years, and has been less than expected due to minimal intrastation flights Fuel use by helicopters is reasonably stable Fuel use does not include aviation ground-support elements		

Recent trends
- ↗ Improving
- ↙ Deteriorating
- — Stable
- ? Unclear

Confidence
- ● Adequate high-quality evidence and high level of consensus
- ◒ Limited evidence or limited consensus
- ○ Evidence and consensus too low to make an assessment

Grades

Very good	No risk of pollution and contamination of environment
Good	Low risk of pollution and contamination of environment
Poor	Medium risk of pollution and contamination of environment
Very poor	High risk of pollution and contamination of environment

2.4.2 Contaminated sites and pollution

In the AAT, contaminated sites are largely a relic of the past (before the Madrid Protocol in 1991) when nonburnable rubbish was dumped at various locations near the stations, or was disposed of by leaving it on the sea ice until it broke out. The old rubbish sites contain a variety of materials, including wood, assorted metals and batteries, and hydrocarbons such as fuel oils and lubricants. Because of past practices of dumping on the sea ice, this waste material is in both the terrestrial and nearshore marine environment. Some contaminants are known to be present in quantities that are hazardous to the environment and although they might be frozen in place for much of the year, they can be dispersed and transported away from the dump site into the surrounding environment; for example, by the flush of melt water that occurs each summer as the winter snows retreat. Studies have shown that hydrocarbons have accumulated in the sediment of bays near Casey Station.[176-177]

The largest potential source of new pollution is the very large quantities of fuel that provide power for stations and vehicles. There is always the risk of oil spill when transporting or storing fuel and this is particularly so in Antarctica, where the climate makes all operations more difficult. Land-based fuel spills, some as large as 90 000 litres, have occurred either through mechanical failures or human error during refuelling or transfer from ship to shore (J Stark, Australian Antarctic Division, pers. comm., April 2011). Occasionally, fuel storage tanks have leaked during winter and the leaks have gone unnoticed until the summer melt reveals that they have drained their contents. Today, all tanks are bunded; that is, the tanks are surrounded by a secondary containment that restricts dispersion of fuel should a leak occur. Hence, the environmental damage is reduced or avoided altogether.

Before a site can be cleaned, it needs to be assessed to determine whether clean-up can be achieved without creating more environmental harm from the disturbance of the site. Chemicals present are identified and their concentrations determined. Currently, a number of tip sites and old fuel spill sites are at various stages of assessment and several fuel spills are being remediated (T Spedding, Australian Antarctic Division, pers. comm., April 2011). Research is also being carried out to determine the maximum possible concentrations of chemicals that will have no measurable impact on the environment—this type of information is commonly used elsewhere in the world as targets for remediation works but, until now, site-specific, risk-based remediation end points have not been available for the Antarctic environment.

Despite the large distances that separate Antarctica from the rest of the world, pollution generated elsewhere on Earth can also travel to Antarctica by air or water. Some persistent organic pollutants, such as the insecticide DDT, can be selectively transported to the polar regions through the process known as global distillation. This process occurs when volatile chemicals evaporate in the warmer places in which they are used and condense in colder places.

The persistent organic pollutants that reach Antarctica by long-distance transport are not yet known to be present in the region in sufficient quantities to cause environmental damage; however, these chemicals do not occur naturally and have toxic properties that can be hazardous to organisms. Antarctica provides an important site for monitoring global background levels of known contaminants that are controlled by the Stockholm Convention on Persistent Organic Pollutants, and also serves as an early warning of the global environmental build-up of new and emerging contaminants.

Southern elephant seal (*Mirounga leonine*) in kelp at Australian National Antarctic Research Expeditions research station, Macquarie Island
Photo by Nick Rains

Box 7.7 Clean-up of the rubbish tip at Thala Valley

The Thala Valley tip was used for disposal of waste from 'Old' Casey Station. The site is near the current Casey Station and contained waste that accumulated before Australia started returning all waste to Australia in the mid-1980s. The Protocol on Environmental Protection to the Antarctic Treaty 1991 (Annex III, Article I) established an international obligation for past and present waste-disposal sites to be cleaned up by the generators of such waste. The management measures of the protocol are enacted into Australian law through the *Antarctic Treaty (Environment Protection) Act 1980*, and its associated Regulations.

In the early 1990s, Australia undertook a preliminary assessment of contaminated sites at each of its stations in Antarctica and on Macquarie Island. The Thala Valley tip was identified as a priority because it contained high levels of several pollutants, including heavy metals, hydrocarbons (mostly fuel and lubricants) and some asbestos, and because it was hydrologically active, being in the path of a major melt stream that formed each summer and drained into the adjacent Brown Bay.

Studies were undertaken to identify the contaminants and to find technologies to remove the waste safely (e.g. Snape et al.,[178] Townsend et al.[179]). For example, sediment cores were collected in Brown Bay and analysed for introduced contaminants—70–80% of lead isotopes found in the sediments had leached into the bay from discarded batteries.[179] In 2000, suitable remediation technologies were identified for both the onsite environmental management of any remediation works and post-removal treatment of the contaminated waste. This included a custom-designed water-treatment plant capable of separating particulate and dissolved contaminants.[178]

In October 2003, the Australian Antarctic Division began removing waste and contaminated soil from the site. Approximately 834 tonnes of the most highly contaminated material was returned to Tasmania for treatment and disposal. Approximately 530 tonnes of less contaminated material was excavated and stockpiled for removal in subsequent years.

Final removal of the remaining Thala Valley material was completed in 2010–11 with the assistance of the Chinese Antarctic research expeditions, whose resupply vessel was used to transport the remaining material[168]—purpose-built containers were filled with the waste and shipped to Fremantle in March 2011. Permission had been obtained from the Western Australian Department for Conservation and Land Management and the Eastern Metropolitan Regional Council to deep-bury the 1005 tonnes of waste returned from Antarctica in 2011 in a Class 4 landfill site. The last burial took place on 7 April 2011.

All works were carried out in accordance with the requirements of Australian quarantine and environmental protection, as well as those of the protocol. The remediated Thala Valley area will be monitored for several years to ensure that remediation goals have been achieved, that site restoration is complete, and to determine whether the previously degraded marine environment of Brown Bay has recovered after removal of the tip.

This project required the Australian Antarctic Division to develop new techniques for remediation of contaminated soils in Antarctica, as well as new ways to monitor the environmental impact. Australia has shared the lessons learned with other nations at a number of international meetings, including the Antarctic Treaty Consultative Meetings, with the hope that this knowledge will assist other Antarctic countries to clean up their contaminated sites.

Abandoned waste at the Wilkes Tip, Thala Valley, near Casey Station (photo by Mike Whittle, Australian Antarctic Division, © Commonwealth of Australia)

Loaded waste container for return to Australia (photo by Sally Chambers, Australian Antarctic Division, © Commonwealth of Australia)

7.7 Assessment summary

State and trends of contaminated Antarctic sites

Component	Summary	Assessment grade (Very poor / Poor / Good / Very good)	Recent trend	Confidence: In grade	Confidence: In trend
Thala Valley	Terrestrial section of Thala Valley clean-up finalised; some material still left in nearshore and marine environment	Very good	↗	●	●
Old Casey Station	Historical fuel spill (1980s)	Poor	—	●	●
Casey Station main powerhouse	Fuel spill at main powerhouse (1999); contaminants reached the melt lake from which fresh water is obtained for the station	Good	↗	●	●
Wilkes Station	Abandoned station (built in 1957); old tip site and fuel cache still present and contain a large volume of contaminated material	Poor	—	●	●
Davis Station tip site	Old tip site	Poor	—	◒	◒
Mawson Station tip site	Old tip site, large land-based debris removed; some material still left in nearshore marine environment	Poor	—	◒	◒
Macquarie Island fuel farm	Historical fuel spill (1980s)	Good	↗	●	●
Macquarie Island main powerhouse	Historical fuel spills (1980s–2000)	Good	↗	●	●

Recent trends
- ↗ Improving
- — Stable
- ↙ Deteriorating
- ? Unclear

Confidence
- ● Adequate high-quality evidence and high level of consensus
- ◒ Limited evidence or limited consensus
- ○ Evidence and consensus too low to make an assessment

Grades

Very good	Remediation activities completed; remediation monitoring continues
Good	Remediation in progress and/or containment of contaminants achieved
Poor	Preliminary impact assessment under way including identification of contaminants
Very poor	No action yet

2.5 Heritage values

Antarctica's unique environment is internationally recognised, and a wide range of its heritage values are protected under the Madrid Protocol. In addition to the general, continent-wide protection provided by the protocol, extra levels of protection can be applied to areas of outstanding environmental, scientific, historic, aesthetic or wilderness values by a range of frameworks (Table 7.1); for example, by designating them as Antarctic Specially Protected Areas. Sites of particular significance to Australia have also been added to the national heritage lists. Australia's subantarctic islands, which do not come under the Antarctic Treaty, are on the World Heritage List.

2.5.1 Natural heritage

Australia's two subantarctic islands or island groups, Heard Island and McDonald Islands in the Southern Ocean and Macquarie Island in the south-west Pacific, were listed on the World Heritage List and the National Heritage List in 1997 and 2007, respectively, because of their 'outstanding natural universal values'. The inclusion of these areas on the World Heritage List underlines not only the physical and natural values these islands represent, but also their international importance. Moreover, these islands are significant for Australia's Antarctic history, as both contain sites of cultural heritage value.[180-181] Heard Island and McDonald Islands are Australian territory and are managed through the Australian Antarctic Division. Macquarie Island is part of Tasmania and in the care of the Tasmanian Parks and Wildlife Services. However, the division coordinates and manages the maintenance of the station and field huts, as well as logistic operations.

Australia also manages 11 Antarctic Specially Protected Areas, including one at Commonwealth Bay (see Section 2.5.2), as well as two Antarctic Specially Managed Areas (ASMAs): Commonwealth Bay (ASMA 03) and the Larsemann Hills (ASMA 06).

Table 7.1 Status of listings of Australia's natural and historic heritage in Antarctica

Site	Register of the National Estate	National Heritage List	Commonwealth Heritage List	World Heritage List
Natural and historic				
Heard Island and McDonald Islands	Registered 1983	Listed 2007	Indicative property; formal nomination not made	Declared 1997
Macquarie Island	Nature reserve registered 1980	Listed 2007		Declared 1997
Historic				
Mawson's Huts and Mawson's Huts Historic Site	Registered 2002	Listed 2005	Listed 2004	
Wilkes Station	Indicative property; formal nomination not made			
Davis Station	Registered 1999		Indicative property; formal nomination not made	
Mawson Station	Registered 2001		Listed 2004	

2.5.2 Historic heritage

Significant sites associated with cultural heritage can be found in the AAT, on Heard Island and Macquarie Island in the Southern Ocean. There are four key types of cultural heritage sites in the region,[182] associated with:

- early scientific endeavour and exploration (1911–14)
- the sealing industry on Heard Island and Macquarie Island
- the British, Australian and New Zealand Antarctic Research Expedition (1929–31)
- Australian National Antarctic Research Expeditions and agencies of other nations that established research stations in the AAT after World War 2.

Any conservation work on the historic sites is assessed for its impact under the *Antarctic Treaty Environment Protection Act 1980*. The *Environment Protection and Biodiversity Conservation Act 1999* also has application, because wildlife occurs within the protected areas. Rather than being managed onsite, some artefacts are recovered from Antarctica for conservation treatment or protection. These artefacts include books, clothing, scientific and mechanical devices, field equipment and many others that, if left in situ, would deteriorate and be lost. These items are catalogued in the Antarctic Heritage Register housed in the data centre of the Australian Antarctic Division.[d]

One of Australia's most important historic sites of international significance is Mawson's Huts, which were erected at Cape Denison, Commonwealth Bay, in 1911 by the men of the Australasian Antarctic Expedition under the leadership of Sir Douglas Mawson. The expedition was the first major and, as it turned out, most dramatic, scientific program of the young nation and, at the time, was important for the application of new technologies, such as the use of wireless transmissions between Antarctica and the outside world via a relay post at Macquarie Island. The expedition collected a wealth of biological, magnetic, geological and meteorological data.

The base that Mawson and his team established at Cape Denison in 1912 was never intended to be a long-term establishment. While the huts were solidly built and survived the Antarctic conditions for many decades, wind ablation and snow intrusion have taken their toll and the structural elements of the site have been deteriorating since their construction. The main hut and the magnetograph house are in sound condition, and the integrity of their interiors is high. In 1998, the magnetograph house was altered by timber cladding on the roof. The transit hut and absolute magnetic hut are in poor condition; both huts have been stabilised to preserve them as standing ruins. The Memorial Cross is in good condition.[183] Most of the portable artefacts outside the huts are still in the same locations they were in when Mawson left the site in 1914.[182,184]

In 2005, the Australian Government registered the four huts on Australia's National Heritage List as Mawson's Huts and Mawson's Huts Historic Site and launched a conservation management plan to protect the site. The management plan was also a requirement under the Madrid Protocol, as the site had been proposed to be nominated as a Historic Site and an Antarctic Specially Managed Area (ASMA 03). Furthermore, the site was declared an Antarctic Specially Protected Area (ASPA 162) embedded within the ASMA, to afford further protection. All access and activities within the ASPA are regulated by a permit system.

In addition to Mawson's Huts, several sites within the AAT are formally protected under the Antarctic Treaty System through their designation as historic sites and monuments (Table 7.1). These include buildings at Mawson and Davis stations, and rock cairns erected by Sir Douglas Mawson at Proclamation Island, Enderby Land and Cape Bruce. Another cairn erected by Sir Hubert Wilkins in 1939 is located in the Vestfold Hills, Ingrid Christensen Coast. A further nine historic sites and monuments have been declared under Antarctic Treaty provisions to protect sites of significance to the United States and Russia.

Most sealing industry sites are on the coast and at risk from the effects of the extreme weather, climate change and a dynamic coastline, as well as human interference and encroachment by vegetation. At Heard Island, a significant amount of cultural heritage material has been lost or has had to be relocated since recording of the cultural heritage began in the mid-1980s. Many of the portable artefacts are slowly deteriorating and only have a limited lifespan.[185] Many sites on Macquarie Island are now partially buried. Shipwreck material, structural elements and portable artefacts are slowly deteriorating.[182,186-187] Ruins of the masts and huts on Wireless Hill survive but are deteriorating.[182,187-188] One of the remaining masts was removed in 2011. Most Australian National Antarctic Research Expedition buildings at Buckles Bay are intact and in good condition.

d data.aad.gov.au/aadc/artefacts

7.8 Assessment summary

State and trends of listed or specially protected sites in Antarctica

Component	Summary	Assessment grade: Very poor	Poor	Good	Very good	Confidence: In grade	In trend
Heard Island and McDonald Islands	Retreating glaciers open potentially new habitat for flora and fauna; visits to the island are infrequent, making monitoring difficult			?		◒	◒
Macquarie Island	Rodent and rabbit eradication program began in 2010 is ongoing; if successful, the island is largely expected to be able to restore itself		↗			●	●
Taylor Rookery (ASPA 101)	Contains one of only three known emperor penguin colonies located on land. The population of penguins has been monitored annually since 1988 and some historical information is also available			—		●	●
Rookery Islands (ASPA 102)	Six different seabird species are breeding on the islands A very small colony of southern giant petrels is one of only four known colonies in East Antarctica			—		◒	◒
Ardery Island and Odbert Island (ASPA 103)	These islands provide breeding habitat for several species of petrel and are examples of their habitat. Visits to the islands are infrequent and no regular census work is done			?		◒	◒
North-East Bailey Peninsula (ASPA 135)	Scientific reference site for vegetation typical of the area. A number of flora studies were conducted in the 1980s. Changes to snow availability appear to put local vegetation under water stress			↙		◒	◒
Clark Peninsula (ASPA 136)	Designated to protect the largely undisturbed terrestrial ecosystem that includes associations of macrolichens and bryophytes. There is also a colony of Adélie penguins. Possibly similar issues with regard to water resources as ASPA 135, but so far there is insufficient evidence			?		◒	◒
Marine Plain (ASPA 143)	The area is representative of an important ice-free terrestrial ecosystem The area contains important sites for studying the palaeoecology and palaeoclimate			?		◒	◒

Component	Summary	Assessment grade (Very poor / Poor / Good / Very good)	Confidence: In grade	Confidence: In trend
Frazier Islands (ASPA 160)	A group of three small islands, all of which are occupied by a variety of seabirds, including small colonies of southern giant petrels Trends are difficult to estimate because of a lack of data; a significant change in the population size cannot be demonstrated	Good: —	◒	◒
Scullin and Murray Monoliths (ASPA 164)	The greatest concentrations of breeding seabirds in East Antarctica are found here; bird numbers range from tens to hundreds of thousands Their remote location makes regular visits impossible	Good: ?	◒	◒
Hawker Island (ASPA 167)	The declaration of this area as an ASPA meant that all colonies of southern giant petrels in the Australian Antarctic Territory are now protected	Good: —	◒	◒
Amanda Bay (ASPA 169)	The only large emperor penguin colony in Prydz Bay is located here In the past, few visits were made to this area and insufficient information is available to predict a trend	Good: ?	◒	◒
Larsemann Hills (ASMA 06)	Two major peninsulas represent a significant part of the ice-free fraction of East Antarctica. Two permanently occupied non-Australian stations exist there and a third is under construction	Good: ?	◒	◒

Recent trends

- ↗ Improving
- ↙ Deteriorating
- — Stable
- ? Unclear

Confidence

- ● Adequate high-quality evidence and high level of consensus
- ◒ Limited evidence or limited consensus
- ○ Evidence and consensus too low to make an assessment

Grades

Very good	Component in excellent state and management plan in place
Good	Component is undergoing conservation work if needed and/or management plan in place
Poor	Component in poor condition but can be rescued; no management plan in place
Very poor	Heritage component is damaged beyond repair

ASMA = Antarctic Specially Managed Area; ASPA = Antarctic Specially Protected Area

7.9 Assessment summary

State and trends of the historic heritage in Antarctica

Component	Summary
Mawson's Huts (ASPA 162), Commonwealth Bay (ASMA 03)	Site undergoing extensive conservation work in accordance with the management plan
Old Mawson Station	Management plan is being prepared Biscoe hut restoration nearly completed
Old Davis Station	Donga line removed; a number of buildings currently under repair Ongoing routine maintenance
Heard Island and McDonald Islands	Oil barrels and sealers graves deteriorating; visits are infrequent, making monitoring activities challenging A management plan is in place
Macquarie Island	A number of old structures removed, but the remains of oiling and sealing tryworks are still on the island

Assessment grade: Very poor, Poor, Good, Very good

Confidence: In grade, In trend

Recent trends
- Improving
- Deteriorating
- Stable
- Unclear

Confidence
- Adequate high-quality evidence and high level of consensus
- Limited evidence or limited consensus
- Evidence and consensus too low to make an assessment

Grades
- Very good: Component in excellent state; management plan in place
- Good: Component is undergoing conservation work; management plan in place
- Poor: Component in poor condition but can be rescued; management plan in place
- Very poor: Heritage component is damaged beyond repair

ASMA = Antarctic Specially Managed Area; ASPA = Antarctic Specially Protected Area

3

Pressures affecting the Antarctic environment

As detailed in Chapter 2: Drivers, the key drivers on the environment are population and economic growth, and climate change. Antarctica, as the only continent without a native human population, has been subjected to less pressure from human activities than other continents. However, the southern continent and its surrounding seas and islands have not escaped the effects of these activities. For example, the atmosphere above Antarctica experienced a major change due to the release of chlorofluorocarbons in the 20th century, which resulted in the development of the ozone hole. The establishment of permanent stations impacts on the local environment, and pollution elsewhere on our planet finds its way even to Antarctica: traces of DDT and its derivatives were discovered in the shells of Adélie penguin eggs in the mid-1960s.[189] A number of vertebrate populations were hunted to near extinction, and economic activities such as fishing and tourism have all had an impact.

What is most likely to have the most lasting impact is the increasing amount of carbon dioxide produced by human activities. The Southern Ocean is absorbing vast quantities of carbon dioxide, leading to a change in the ocean's chemistry that has the potential to affect organisms and their lifecycles in a variety of ways. Increased atmospheric carbon dioxide is also producing climate change. We have seen a warming of surface temperatures initially restricted to the Antarctic Peninsula, where surface temperatures increased by 0.56 °C per decade over the past 50 years,[190] while the global temperature increase averaged 0.13 °C per decade.[6] This warming has led to the collapse of most of the ice shelves in the peninsula region,[58] retreating glaciers[191] and a decrease in the extent of sea ice in the Bellingshausen Sea.[192]

At a glance

Antarctica is changing at an increasing rate due to global warming. The most rapidly changing region is West Antarctica, particularly around the Antarctic Peninsula, where temperatures have risen by 5 °C over the past five decades. Until recently, the environmental variables were thought to be more stable in East Antarctica where Australia operates. However, there is compelling evidence that change is occurring here as well, and while it is currently at a slower rate than in West Antarctica, the rate of change is expected to increase over the coming decades. The changes will affect the marine and terrestrial ecosystems of the region, probably profoundly, in the coming decades.

Human activities are still increasing; new stations are being constructed, often in rare ice-free areas. Tourism is still a major activity around the Antarctic Peninsula. Disturbance of habitat and wildlife, the introduction of invasive plants and pollution are all risks linked to human presence on the continent.

Extreme weather events are likely to increase in frequency and perhaps in intensity as the planet warms. Antarctica is known for its high winds and intense storms. However, in certain regions, rain is now occasionally falling where it only ever used to snow. These events too are changing the Antarctic environment and biodiversity.

Until recently, East and West Antarctica appear to have responded differently to the influences of climate change (see Section 2.1.2). While only West Antarctica experienced warming conditions for several decades, changes in near-surface temperatures across the entire continent have now been estimated at 0.12 ± 0.10 °C per decade.[38] Increasing air and ocean temperatures cause changes in snow-fall patterns, which in turn affect the quality of sea ice, as well as its extent and durability. For example, near Davis Station, a long-term monitoring study of sea ice detected a delay in the time when the maximum thickness is reached by the fast ice, and attributed this trend to the warmer winters in recent years.[193]

Assessing the overall impact that climate change will have on Antarctic systems is difficult, however, because there is a lack of data for large parts of the continent; timeseries tend to be too short or available only for a small number of locations. The processes driving weather patterns and underlying climate change are complex, because they can operate on different time and spatial scales, and may lead to positive or negative feedback loops as they either increase or counteract each other.

Connections between, for example, atmospheric and oceanographic phenomena are also still poorly understood.

Similarly, while it is highly likely that climate change will alter ecosystems, the processes involved are complex and not fully understood. Currently available biological models are even less sophisticated than physical ones; models of the Southern Ocean's food webs fall short in linking dynamics at the base of the food web to physical models of the oceans.[194] Predicting how organisms will respond individually or collectively to climate change and other human-induced pressures is a major challenge of research today. We do not know which species may be able to adapt to the evolving environment through genetic responses. Some organisms may benefit from the effects of climate change—at least in the short term. For example, more ice-free areas offer a potential habitat for plants and animals. However, the long-term consequences are hard to predict.

The restoration of ozone levels will also have a profound effect on the region. The ozone hole is expected to vanish in the next three decades. This will reduce ultraviolet levels, to the advantage of many species (see Section 2.3.1). Ultraviolet radiation was 55–85% higher at the South Pole during 1991–2006 compared with 1963–80.[40] However, the ozone hole has largely protected East Antarctica from global warming. The loss of stratospheric ozone cooled and changed the atmospheric circulation. A recovery of the ozone hole will reverse these processes and significantly increase the warming trend in East Antarctica.

3.1 Pressures on the marine environment

The water chemistry of the Southern Ocean appears to be changing at a faster rate than previously estimated, particularly in the deep ocean layers. In the cold Southern Ocean, carbon dioxide is being sequestered at a higher rate than in subtropical waters. Increases in carbon dioxide cause an acidification of ocean waters that make it difficult for shell-building organisms to extract the calcium they need from the ocean (see Section 2.3.1).

Changes in the physical ocean environment are likely to affect the ocean's productivity, which influences the survival of higher order predators. However, the degree and nature of the effects of global warming on various levels of productivity, as well as on ocean circulation and chemistry, are still unclear. These uncertainties limit the degree to which we can predict the effects of changes in the physical environment and biological production, the rate and direction of change, or the relative importance of various pressures.

3.1.1 Marine species

Wildlife populations have been exposed to change in their environment throughout the history of our planet. Some extreme events led to mass extinctions. However, other changes (for example, changes in atmospheric carbon dioxide) took place slowly over centuries or longer, and often enabled vertebrate species to evolve certain adaptive traits.[195] By contrast, the current climate change is occurring at an unprecedented and increasing rate, leaving many species vulnerable because their capacity to adapt operates much more slowly. Also, the changes are not constant but often vary with region and may differ in their timing and scale. Species differ significantly in their ability to adapt, their generation time and longevity, reproductive output and success, and more. A particular problem occurs where the lifecycle of a prey species loses its synchronicity with dependent predators and food becomes less available at key times (e.g. onset of breeding, weaning or fledging of young). The inherent differences of species, plus a lack of understanding of how various environmental factors may interact, make it almost impossible to predict the fate of particular species and populations.[195]

Organisms can react to their changing environments in three main ways:

1. Species shift to areas where the conditions are still similar to those they encountered previously and where adaptations are not required. Movement of species at the Antarctic Peninsula is possible: as the northern parts become warmer, affected species may move further south. However, the size of the Antarctic continent and access to food limit how far they can go. In the southern Indian Ocean, wildlife populations breeding on the subantarctic islands have far fewer options to move south, because there is no intermediate location between the islands and the Antarctic continent. Thus, if they were to shift their distribution, they may have to endure colder conditions than they have so far experienced.

2 Species adapt to live under warmer and perhaps more marginal conditions at their current breeding locations. This might require a shift in their behaviour and physiology to allow them to adjust, for example, the timing of their breeding season, the growth rate of their offspring or even the age of first breeding. In all likelihood, these changes would require a change in their genetic make-up. Which strategy species ultimately choose depends on their degree of adaptability, as well as the rates of change of the various parameters.

3 If species fail to move or to adapt to their altering environment, they will become extinct.[163] Some species are clearly more threatened by the environmental changes than others.

Southern lights, aurora australis, over Macey Hut, Antarctica
Photo by Fred Olivier

The effects of ocean acidification are likely to have severe biological impacts within decades and could dramatically affect the structure and function of marine ecosystems.[27,80,196-199] Such changes would have profound effects on ecosystem services, including the productivity of fisheries. These changes are most pronounced in the polar regions where the acidity of the water is changing twice as fast as in warmer, tropical and subtropical regions.

Antarctic invertebrate communities form a significant part of the marine food web. The responses by invertebrates to ocean acidification are expected to vary with species. Experimental work on temperate marine organisms has demonstrated a wide variety of responses ranging from potentially positive effects, such as increased metabolic rates in autotrophs (organisms that produce their own food from inorganic sources) to negative effects, such as decreased growth rates in sea urchins (see Hendriks et al.[200] for review). Ocean acidification affects the life stages of organisms in different ways.[201] For example, fertilisation of the Antarctic nemertean (ribbon) worm (*Parborlasia corrugatus*) may not be affected by a lowering of the pH, and experimental work showed that even egg development appeared resilient when seawater pH was reduced to neutral.[202] However, abnormalities occurred at a later stage (blastula stage) of the embryos' development.[202] While the pH changes that produced the abnormalities are not predicted to occur in the near future (by 2100) they are expected if the oceans continue to acidify in the long term (by 2300).[202]

The benthic invertebrate communities of Antarctica, especially those living outside the intertidal zone, exist in a very stable environment where temperatures fluctuate—for example, in the high Antarctic—as little as 1.5 °C throughout the year.[203] These stenothermal (narrow temperature) environments came into existence about 4–5 million years ago as the waters surrounding Antarctica cooled.[204] How a warming of the ocean may affect organisms adapted to live in a very narrow temperature range is difficult to predict. Many invertebrates die or cannot perform crucial biological activities when temperatures are raised 5–10 °C.[204] However, these results are based on experiments during which temperatures are increased rather quickly. The more gradual the environmental change, the better are the chances of at least some species adapting to the modifying conditions.

7.10 Assessment summary

Pressures affecting Antarctic marine species

Component	Summary	Assessment grade				Confidence	
		Very high impact	High impact	Low impact	Very low impact	In grade	In trend
Increases in ocean carbon dioxide	Primary production by some species may increase up to 19%, but overall increase is likely to be small			—		◒	◒
Ocean acidification	Concentrations of nutrients and rates of calcification will decrease, causing changes in microbial composition, production and nutritional value			↙		◒	◒
Ultraviolet B radiation	Interspecific differences in response but can reduce production, slow growth, limit survival and change species composition			↙		●	●
Sea surface temperature	Surface warming may increase stratification, increase exposure to ultraviolet B radiation, reduce surface nutrient supply and change interactions among key species, causing changes in microbial composition and production. A latitudinal shift in productivity is predicted. There is also increased potential for invasion of alien species			↙		◒	◒
Sea ice extent	Regional differences exist. Decreases in sea ice may reduce microbial food available to grazers (e.g. krill) and carbon dioxide draw-down; altered light climate will favour earlier, weaker blooms					○	○

Component	Summary	Assessment grade: Very high impact	High impact	Low impact	Very low impact	Confidence: In grade	In trend
Sea ice thickness	Thinning alters the light regime; higher light intensities may reduce productivity of light-sensitive species					○	○
Marine pollution	Persistent organic pollutants and inorganic pollutants from local and exogenous sources exist; some are expected to increase and may have direct and indirect toxicological effects on Antarctic organisms Near the stations, the impact is localised and comes mainly from old tip sites			?		●	●

Recent trends

- ↗ Improving
- ↙ Deteriorating
- — Stable
- ? Unclear

Confidence

- ● Adequate high-quality evidence and high level of consensus
- ◒ Limited evidence or limited consensus
- ○ Evidence and consensus too low to make an assessment

Grades

Very low impact	Communities are not affected by changes; operate at maximal reproductive capacity
Low impact	Few communities are affected and operate below maximal reproductive capacity; structure and function of system/community not impaired
High impact	Some communities are affected and operate well below maximal reproductive capacity; structure and function of system/community impaired
Very high impact	Affected communities barely functional

3.1.2 Commercial fisheries

The largest commercial fishery in the Southern Ocean is for Antarctic krill. This fishery is currently concentrated in the South Atlantic Ocean and there is currently no krill fishery in East Antarctica—although there was one from 1974 to 1995. CCAMLR has recently received expressions of interest from fishing companies to fish for krill off the AAT. In 1996 and 2006, the Australian Antarctic Division conducted two major marine science voyages (BROKE in 1996, BROKE-West in 2005–06) to examine the distribution and abundance of krill in East Antarctic waters, and found quantities that could sustain commercial activities.[114] The results of these surveys were used by CCAMLR to set precautionary catch limits on the krill fishery off most of the AAT (80°E to 150°E).

Australian fishing efforts for Patagonian toothfish and, to a lesser extent, mackerel icefish are concentrated around subantarctic Heard Island and McDonald Islands, and Macquarie Island. Commercial fishers operate throughout the year on Heard Island and McDonald Islands, and fishing activities are regulated by the Australian Fisheries Management Authority through CCAMLR. The fishery around Macquarie Island is also managed by the authority because the island falls outside the jurisdiction of CCAMLR, although CCAMLR-like procedures are adopted. Licensed vessels in the subantarctic fisheries show a very high degree of compliance to licence conditions. Australia undertakes regular fish stock assessments for the Heard Island and McDonald Islands region and catch limits, based on the best scientific information available, are adopted through the CCAMLR process.

In the Indian Ocean, illegal, unregulated and unreported (IUU) fishing is currently a significant problem in the high seas off Antarctica and outside the Australian exclusive economic zone at Heard Island and McDonald Islands. Bottom longliners and gillnetters exploit toothfish on the continental slope and submarine banks. In the absence of actual catch rates, it is difficult to determine how much fish is caught by illegal vessels. Based on the best available information, the estimated weight of IUU catches in the entire CCAMLR area was 1615 tonnes in the 2009–10 fishing season (1 December 2009 – 30 November 2010). Of this, about 1340 tonnes were caught in the region that includes the waters off the AAT and Australia's subantarctic islands. This was four times as much as had been estimated in the previous season.[205-206]

While fishing and the legal or illegal extraction of resources is itself a pressure on the Antarctic environment and its species, a number of pressures also affect the fisheries. These include the results of climate change as discussed above, particularly ocean acidification, and other anthropogenic factors, such as pollution.

Antarctic krill (*Euphausia superba*), key species in the Antarctic ecosystem, Antarctica
Photo by Jean-Paul Ferrero

7.11 Assessment summary

Pressures affecting Antarctic fisheries

Component	Summary	Assessment grade (Very high impact / High impact / Low impact / Very low impact)	Confidence: In grade	Confidence: In trend
Extraction of biotic resources	Rapidly increasing catches of krill and new fishing technologies threaten to outstrip the ability to sustainably manage fisheries			
Illegal, unregulated and unreported fishing	Remains a serious problem in the Southern Ocean; impact is difficult to ascertain with accuracy, but it threatens the sustainability of harvested and dependent species			
Ocean acidification	Some marine organisms already affected by ocean acidification, including reduced calcification of shells and exoskeletons; current impact is probably low but expected to lead to measurable changes in the Southern Ocean ecosystem and change in species composition			

Recent trends: Improving; Deteriorating; Stable; Unclear

Confidence:
- Adequate high-quality evidence and high level of consensus
- Limited evidence or limited consensus
- Evidence and consensus too low to make an assessment

Grades

Very low impact	There are few short-term, reversible impacts from this factor
Low impact	There are transitory impacts from this factor but locally restricted
High impact	There are significant impacts from this factor that may become irreversible in future and become effective regionally
Very high impact	There are predicted significant impacts from this factor that are irreversible and impact is regional

3.2 Pressures on the terrestrial environment

As for the marine environment, pressures on the terrestrial environment operating on a global scale include anthropogenic climate change (e.g. atmospheric warming and changes to water regimes), while local pressures include the introduction of alien species and impact from human activities.

Climate change impacts in Antarctica and the subantarctic include changes in trends in climate parameters (such as air temperature, precipitation and wind speed), as well as increased frequency and impact of extreme or pulse events.[207] Both are regionally specific. In Antarctica, flooding from an extreme summer warming event in 2002 altered species abundances in nematode communities in the Dry Valleys,[207] and an extreme warming event in the winter of 2009 negatively impacted moss communities in the Windmill Islands (M Ball, Australian National University, pers. comm., April 2011).

The introduction of alien species has significantly altered the landscape, composition of ecosystems, and species interactions on many subantarctic islands not under Australian jurisdiction.[208] Studies of the flora at the French subantarctic Kerguelen Island date back to 1874 when three introduced plants were collected.[209] Large-scale surveys mainly in the 1970s and 1980s discovered a total of 168 introduced plant species on Possession, Kerguelen and Amsterdam islands. During a survey in 2000, 118 of these were still present. On some islands, the alien species are well established and outnumber the native species. For example, at Kerguelen Island, 68 introduced plant species were present in 2000 compared with only 14 native species.[209] In addition, there are 30 known invertebrate alien species.

On Australia's Macquarie Island, there are only 3 alien plant species but 28 alien invertebrate species. Recent research has suggested that the presence of some alien invertebrates has a negative impact on native invertebrate species richness and density.[210] Australia's McDonald Island appears to be the only island in the subantarctic that is free of introduced species. Nearby Heard Island has one known alien plant, the grass *Poa annua*, and three invertebrate species: the earthworm *Dendrodrilus rubidus*, the mite *Tyrophagus putrescentiae* and the small thrips *Apterothrips apteris*,[211] but no introduced vertebrates.

Climate change and the intrusion of invasive species may combine as pressures.[145,212] As global warming progresses and ambient temperatures rise, non-native species formerly unable to survive in the region may now be capable of establishing themselves and outcompeting the native organisms.[145] New species that become established in a warming environment tend to be more competitive than native species because of better dispersal mechanisms or lack of predators, or may occupy niches that previously did not exist. Under such circumstances, food webs and ecosystem functioning could be altered dramatically (e.g. Convoy & Lebouvier[213]).

Decaying iceberg and Antarctic petrels, Southern Ocean
Photo by Doug Thost

7.12 Assessment summary

Pressures affecting the Antarctic terrestrial environment

Component	Summary	Assessment grade: Very high impact	High impact	Low impact	Very low impact	Confidence: In grade	In trend
Changes in ambient temperature	At the Antarctic Peninsula, populations of two native flowering plants are expanding rapidly; similar observations have been made on subantarctic islands where ice-free areas are increasing; composition of plant assemblages may change		?				
Changes in water availability	In East Antarctica, mosses are drying out rapidly due to ice melt and channel run-off away from existing moss beds		?				
Introduction of alien species and pathogens	Invasive species can have a devastating effect on endemic species and communities. The eradication program currently under way at Macquarie Island will have a positive effect on seabird populations Further warming of the atmosphere may help pathogens to become established		?				
Erosion	More ice-free areas are likely to suffer from erosion, especially on subantarctic islands		?				
Pollution	Deposition of solid and liquid wastes can impact both terrestrial and marine communities. Impacts tend to be localised, but pollutants are also received from nonlocal sources and are likely to contaminate much larger regions		↙				

Component	Summary	Assessment grade (Very high impact / High impact / Low impact / Very low impact)	Confidence: In grade	Confidence: In trend
Wildlife disturbance	Increased visitation puts pressure on wildlife populations; with increasing demands to see wildlife, more areas may be visited more frequently and in greater numbers	? (Low impact)	◒	◒
Physical disturbance and habitat loss	Many human activities significantly alter the natural environment (e.g. stations); visitation can negatively affect habitat through trampling	— (Low impact)	●	●

Recent trends

- ↗ Improving
- ↙ Deteriorating
- — Stable
- ? Unclear

Confidence

- ● Adequate high-quality evidence and high level of consensus
- ◒ Limited evidence or limited consensus
- ○ Evidence and consensus too low to make an assessment

Grades

Very low impact	There are few short-term, reversible impacts from this factor
Low impact	There are transitory impacts from this factor but locally restricted
High impact	There are significant impacts from this factor (may be cumulative); impacts are regional and may become irreversible in future
Very high impact	There are predicted significant impacts from this factor that are irreversible; impact is regional

3.3 Pressures on Antarctic historic heritage

The buildings and structures that make up Australia's historic heritage were built up to 100 years ago. At the time of their construction, they were built to last only a few years (e.g. Mawson's Huts at Commonwealth Bay). It was never anticipated that they would still be standing a century later and considered a valuable part of Australia's Antarctic heritage.

The building materials are vulnerable to deterioration and the greatest threat to the integrity of the buildings and structures lies in the natural elements. Wind, weather, frost, ice and melt water all contribute to the deterioration of buildings. Corrosion, fungal growth, wind and snow loads, exposure to ultraviolet radiation, the freeze–thaw cycle and high relative humidity inside the main hut affect the conservation of structures and artefacts.[182] An artefacts conservation program was instigated in 2008.[214-216]

The illegal removal of artefacts is also a concern. All visitors require permits if they intend to visit the island; however, the region's remoteness—which has protected its natural values—also makes it extremely difficult to control unauthorised access. For example, fishers on illegal fishing vessels operating in the area may visit and remove artefacts.

On the subantarctic islands, the maritime climate promotes corrosion of metal artefacts. Wooden items are abraded by windborne sand and salt particles. Disturbance by wildlife, land erosion and slippage is also a potential problem,[186,217-218] as is erosion and exposure of artefacts. Cultural heritage on the islands may also be damaged by volcanic and seismic activities. Seismic activity has been identified as a specific threat to structures on Macquarie Island, although most of the research expedition buildings have been built to withstand tremors.[182]

Heard Island is a long way from Australia and caring for the components of historic heritage on the island is an enormous challenge. The cultural heritage of Heard Island is conserved through a process of managed decay. This is a pragmatic management option, which acknowledges the practical impossibility of conserving all elements of the cultural environment in a remote area where access is extremely limited.[182,217] Permitted visits are highly infrequent and tend to be restricted to the short summer. The management plan states that heritage values, such as buildings, are and have been in a greatly deteriorated state for a long time and are permitted to disintegrate under the influences of weather and climate. There are several sealers' graves in the south-eastern part of the island, not far from a large king penguin colony. The vegetation cover is dense and continues to engulf and cover the old graves.

A specific risk to Heard Island is the changing coastline. For example, wooden oil barrels that were left by sealers at Oil Barrel Point have disappeared steadily over the past few decades as the barrels have eroded out of the beach cliff.[219] Fewer than a quarter of those recorded in the 1980s are still in place.

Mawson's Huts, Antarctica
Photo by Doug Thost

7.13 Assessment summary

Pressures affecting Antarctic historic heritage

Component	Summary	Assessment grade: Very high impact	Assessment grade: High impact	Assessment grade: Low impact	Assessment grade: Very low impact	Confidence: In grade	Confidence: In trend
Melt water	Fine snow particles penetrate the buildings and fill the buildings; causes structural damage and damage to artefacts		↙			●	●
Wind	Can limit conservation work and destroy weakened structures		↙			●	●
Climate change	Increased wind strength and frequency of storms puts pressure on huts		↙			●	●
Coastal erosion	Dynamic coastline at Heard Island changes and threatens some artefacts		↙			●	●
Fauna and flora	Wildlife such as elephant seals can exert considerable impact when they move across sites Overgrowth by plants on subantarctic islands can lead to obscuring of items, such as the headstones of graves at Heard Island		↙			●	●
Unauthorised collections	Could occur at Heard Island; unauthorised visits possibly occur					○	○

Recent trends
- ↗ Improving
- ↙ Deteriorating
- — Stable
- ? Unclear

Confidence
- ● Adequate high-quality evidence and high level of consensus
- ◒ Limited evidence or limited consensus
- ○ Evidence and consensus too low to make an assessment

Grades
- Very low impact: Component is hardly impacted by factor and requires no further conservation efforts
- Low impact: Factor impacts on part of the component and may require further conservation efforts
- High impact: Factor impacts component moderately and requires further conservation efforts
- Very high impact: Factor impacts component significantly and limits further conservation efforts

4

Effectiveness of Antarctic management

Continually improving the environmental management of Australia's activities and encouraging other states active in Antarctica and the Southern Ocean to do likewise is one of Australia's key Antarctic management priorities.

There are four main types of human activities in the Antarctic region: fisheries, national Antarctic programs, commercial tourism and other nongovernmental activities, such as private expeditions. The Australian Antarctic Division administers Australia's national Antarctic program, which focuses mainly on the East Antarctic region of the continent but also Australia's subantarctic islands and the Southern Ocean. Other countries, for example China, India, Japan, Norway and Russia, also operate in East Antarctica, including within the AAT. Tourism, including by Australian tour operators, occurs mostly in the Antarctic Peninsula region away from the Australian national Antarctic program's main areas of interest.

The Antarctic region and the Southern Ocean are remote from the Australian administrative head office so that management is effectively by 'remote control'. This poses some unique challenges for Antarctic management and emphasises the importance of an effective environmental management regime.

At a glance

Antarctic management is of international concern and is primarily regulated through the Antarctic Treaty and the Convention on the Conservation of Antarctic Marine Living Resources. Australia is committed to protecting the values of Antarctica and adhering to all environmental protection measures through the Antarctic Treaty System, and leads efforts in the Commission for the Conservation of Antarctic Marine Living Resources. Australia develops, implements and manages practical ways to minimise the effects of our Antarctic activities; for example, by restoring past worksites and cleaning up historical waste sites. Australia also plays a significant role in combating illegal, unregulated and unreported fishing in the Southern Ocean.

Research ensures that management of activities in Antarctica and the Southern Ocean is based on sound scientific principles and the best available scientific knowledge. Australia's research contributes to understanding how environmental systems function and how global climate change affects the Antarctic environment.

While climate change cannot be mitigated through the management of activities in Antarctica, Australian research is helping to inform strategies to maximise the resilience of the Antarctic environment and ecosystems.

4.1 Governance

As detailed in Section 1.3, the Antarctic Treaty System is the primary international governance framework for the Antarctic region. Australia's engagement within the international forums of the Antarctic Treaty System supports Australia's objectives for protection and management of the Antarctic region, including the AAT, as do a number of pieces of legislation within Australia. Other legislation and organisations are specifically responsible for managing the marine environment.

4.1.1 International engagement

Internationally, Australia has taken a leading role in promoting environmental protection within the Antarctic Treaty System since its inception. Australia actively participates and leads discussions in key Antarctic international forums that include the Antarctic Treaty Consultative Meeting, the Committee for Environmental Protection, CCAMLR, the Council of Managers of National Antarctic Programs, and the Agreement on the Conservation of Albatrosses and Petrels.

4.1.2 Australian legislation

The obligations contained within Australia's international agreements are incorporated into Australian domestic law. The legal regime for the AAT is established in the *Australian Antarctic Territory Act 1954*. The *Antarctic Treaty Act 1960* gives effect to the Antarctic Treaty. Other Australian legislation implements parts of the Antarctic Treaty System into Australian law, including the *Antarctic Treaty (Environment Protection) Act 1980*, which gives effect to the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol) and sets out environmental protection obligations for all activities in the Antarctic Treaty area. The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) applies to activities undertaken on Australian land (such as the AAT), including those that may have significant impact on matters of national environmental significance. The Convention on the Conservation of Antarctic Marine Living Resources is implemented in domestic law through the *Antarctic Marine Living Resources Conservation Act 1981*.

The legal regime for Heard Island and McDonald Islands is established in the *Heard Island and McDonald Islands Act 1953*. Under that Act, the *Environment Protection and Management Ordinance 1987* provides for the protection of the environment and controls access to the territory. The territory is also a proclaimed Commonwealth Reserve under the EPBC Act and all activities in the territory must be in accordance with the Heard Island and McDonald Islands Marine Reserve Management Plan.

The Macquarie Island Commonwealth Marine Reserve is adjacent to the Macquarie Island Nature Reserve, which is managed by the Tasmanian Government. The marine reserve is subject to the EPBC Act with activities in the reserve governed by the Macquarie Island Commonwealth Marine Reserve Management Plan. This plan is currently under review and interim management arrangements under the EPBC Act apply until a new management plan is in place.

4.1.3 Marine environment

(This section relates to international agreements of relevance to the Antarctic marine environment other than the Convention on the Conservation of Antarctic Marine Living Resources and the Antarctic Treaty/Madrid Protocol, which are the primary instruments).

The International Whaling Commission was established in December 1946 when the International Convention for the Regulation of Whaling was signed by 15 nations, including Australia. The commission operates independently from the Antarctic Treaty System. Currently, there are 89 member nations, and annual meetings are held in the various member countries. A committee of about 200 whale biologists offers scientific advice to the commission.

Seals living in Antarctic waters are protected and managed under agreements separate from the Convention on the Conservation of Antarctic Marine Living Resources. The Convention for the Conservation of Antarctic Seals is part of the Antarctic Treaty and was entered into force generally in 1978 and for Australia in 1987. This convention applies to all earless seals, as well as all southern fur seals (*Arctocephalus* spp.) Currently, there is no commercial sealing.

The International Maritime Organization (IMO) is a United Nations agency that provides international standards for the operation and regulation of shipping and has been active since 1948. The Marine Environment Protection Committee (MEPC) is the main technical committee of the IMO that deals with the prevention and control of pollution from ships. In Australia, the Australian Maritime Safety Authority engages in the work of the MEPC. The International Convention for the Prevention of Pollution from Ships (MARPOL) is the most important tool of the MEPC in their regulation and prevention of pollution of the oceans. In recent years, a number of vessels operating in the Antarctic Peninsula region reported incidents that highlighted the risk of pollution by heavy fuel oils. Heavy fuel oils are hazardous to the environment because they break down more slowly than other fuels. In 2005, the parties to the Antarctic Treaty initiated discussions with the IMO to limit the use of heavy fuel oils in ships sailing to Antarctica. An amendment to MARPOL 73/78 Annex I that bans the use of heavy fuels in the Antarctic area entered into force on 1 August 2011.

4.2 Management processes

Several processes contribute to the overall management of the Antarctic region, including the framework provided by protected areas, as well as activities on the stations and in the field.

4.2.1 Protected areas

Under the Madrid Protocol, certain areas receive a higher level of protection if they have outstanding environmental, scientific, historic, aesthetic or wilderness values. The parties to the Antarctic Treaty have developed guidelines for assessing areas suitable as Antarctic Specially Protected Areas (ASPAs), and for preparing the required management plans, which are submitted by the proposing party to the Committee for Environment Protection and approved at an Antarctic Treaty Consultative Meeting. The management plans contain information on the reasons for designating an area as an ASPA. They also identify restricted zones, the conditions under which permits may be granted, as well as the conditions under which an area may be accessed and what kind of activities may be conducted. Regular reviews—every five years—help to determine whether the management objectives are achieved and the values are preserved. Entry into an ASPA is prohibited unless a permit has been issued either by the Australian Antarctic Division or the equivalent government department of other countries.

Australia administers management plans for 11 ASPAs in Antarctica, and is also responsible for implementing the Heard Island and McDonald Islands Marine Reserve Management Plan, and the Mawson's Huts Historic Site Management Plan.

4.2.2 Australian Antarctic Division environmental management system

In 2002, the Australian Antarctic Division became the first national Antarctic program to implement an environmental management system certified to the international standard ISO 14001. The environmental management system continues to provide a framework for the systematic management of the ways in which the Australian Antarctic program interacts with the environment.

Each station has a nominated environmental officer who is responsible for reporting issues as they occur and suggesting improvements in the way activities are carried out. However, there is recognition that environmental protection is everybody's responsibility. A web-based reporting system allows any expedition member to submit information or suggestions on environmental issues.

4.2.3 Training and awareness

The Australian Antarctic Division, as lead agency for Australia's Antarctic program, ensures that everyone involved in the program is aware of their personal responsibility to care for the environment. At appointment, all expeditioners must agree to abide by a code of personal behaviour, which includes a practical commitment to Australia's environmental management responsibilities. Induction and training of new employees includes an introduction to the relevant Australian laws and the division's approach to environmental matters. At Australia's Antarctic and subantarctic stations, the station leader is responsible for environmental management and is assisted by the station environment committee, a station environmental officer and a station waste-management officer.

4.3 Management achievements

Australian officials actively participate in the international forums of the Antarctic Treaty System to promote improved environmental protection and conservation outcomes for the Antarctic region.

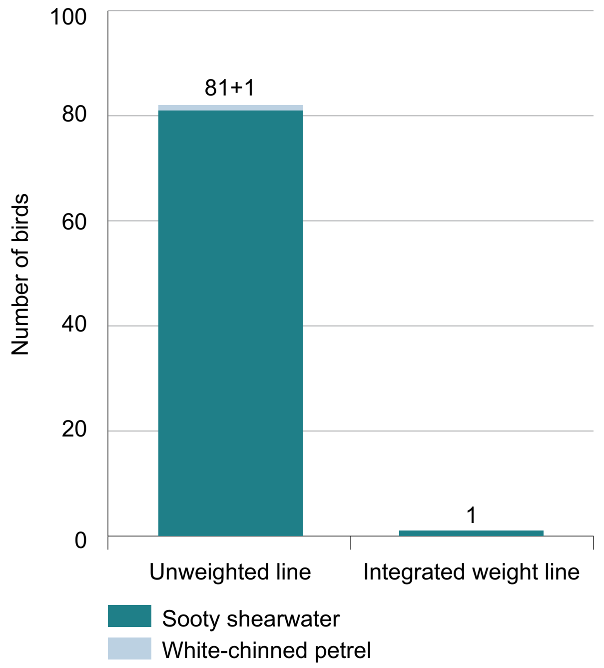
Examples of management achievements in recent years include:

- Australia co-convened a Committee for Environmental Protection workshop in 2006 on Antarctica's Future Environmental Challenges, which led to the development of a strategic work plan for the committee. Highest priorities currently include removing non-native species and preventing new introductions, climate change, tourism and area protection.
- In 2007, parties to the Antarctic Treaty approved an Australian-led proposal to establish an Antarctic Specially Managed Area (ASMA) in the Larsemann Hills region of East Antarctica, with the objective of promoting cooperation and collaboration between the parties that are active in the region (Australia, China, India, Romania and the Russian Federation).
- In 2008, Australia led an international review of the environmental aspects of China's proposal to establish a new research station at Dome A, within the AAT. Australia led a similar review in 2011 of the Republic of Korea's proposal to establish a new station in the Ross Sea region of Antarctica.

- The 2010 Antarctic Treaty Meeting of Experts on Climate Change and Implications for Antarctic Management and Governance and the subsequent Antarctic Treaty Consultative Meeting endorsed Australia's assessment of climate change implications for current and future Antarctic infrastructure, logistics and environmental values, and agreed that other parties to the Antarctic Treaty should undertake and report on similar assessments.
- In 2010 and 2011, Australia conducted official inspections of several Antarctic facilities operated by other parties, including assessing compliance with the provisions of the Antarctic Treaty and Madrid Protocol.
- Australia held the Chair of the Committee for Environmental Protection from 2003 to 2006, and since 2008 has held the position of committee Vice-Chair. Since 2008, Australia has also led an official subsidiary body of the committee, established following an Australian proposal, with the objective of improving the effectiveness of management plans for ASMAs and ASPAs.
- In CCAMLR, Australia has played a leading role in discussions about how to improve the conservation of Antarctic marine living resources. For example, in 2006, CCAMLR prohibited the use of bottom trawling gear in areas shallower than 550 metres in the high seas areas of the convention area. CCAMLR also now requires an assessment of impacts on bottom environments before any fishing activities occur. Following an Australian proposal in 2006, CCAMLR prohibited the use of deep-sea gillnets in the convention area. Directed fishing for sharks has also been prohibited by CCAMLR. Australia's patrol presence in the Heard Island and McDonald Islands region has resulted in no reported IUU fishing activity in the Heard Island and McDonald Islands exclusive economic zone since 2004–05.
- A CCAMLR Conservation Measure was adopted to increase cooperation between CCAMLR and noncontracting parties to undertake more coordinated capacity building, including in port and flag states. Australia co-sponsored a successful proposal to CCAMLR that resulted in a productive workshop in Africa in 2010 to build capacity among African states that have engaged in IUU fishing or IUU-related activities.

In recent years, there has been near zero seabird bycatch by legal fishers operating in commission-managed fisheries. However, bycatch of seabirds, including endangered albatrosses and petrels, remains unsustainable in the Southern Hemisphere. All 22 species of albatross protected under the Agreement on the Conservation of Albatrosses and Petrels are now listed by the International Union for Conservation of Nature as threatened. It is estimated that worldwide up to 300 000 seabirds are killed each year during interactions with coastal and high seas fisheries. Coastal fisheries are subject to state legislations and fisheries regulations; in contrast, high seas fisheries are open access operations. Although the high seas have been divided into management areas of various regional fisheries management organisations, the incentives to avoid overexploitation and to operate sustainably are weak.[220] Many of the high seas tuna fisheries, including in the Pacific, Atlantic and Indian oceans, have failed to adopt and effectively implement the known effective bycatch mitigation measures. Bycatch from IUU fishing is difficult to estimate but known to occur at a higher rate than from legal fisheries due to the likely absence of bycatch mitigation measures. Australia, through its active engagement with the Agreement on the Conservation of Albatrosses and Petrels and other international forums (including CCAMLR and regional fisheries management organisations) is actively pursuing the adoption of sustainable fishing practices that minimise seabird bycatch (Box 7.8).

Box 7.8 How science, policy and industry can help our seabirds



Source: Data from Robertson et al.[224]
Design by Barbara Wienecke, Australian Antarctic Division

Figure A Longlines with integrated weight sink much faster than normal (unweighted) gear and greatly reduce seabird mortality

White-chinned petrels are the most common seabird species killed in longline fisheries in the Southern Hemisphere; every year, tens of thousands are caught in commercial longline operations (photo by Simon Bennet, Australian Government Department of Sustainability, Environment, Water, Population and Communities)

Seabirds have long suffered high mortality rates in interactions with commercial fishing operations throughout the Southern Hemisphere.[221-222] This is primarily due to longlines, where birds are attracted by the baited lines, become hooked and drown. For example, since 2002, about 40 000 white-chinned petrels (*Procellaria aequinoctialis*) alone were killed mainly on longlines set in the southern Indian Ocean near Crozet and Kerguelen islands. Many thousands of seabirds were also killed in fishing areas managed by the Commission for the Conservation of Antarctic Marine Living Resources. However, during their annual meeting in 2009, the commission announced that only two seabirds had been killed by legally operating demersal toothfish longliners in commission-managed waters (seabird deaths were reduced in the subantarctic but remained high). This was truly remarkable given that some 32 million hooks had been set to catch toothfish.[223]

This achievement was due to the collaboration of scientists, policy makers and industry members wanting to reduce the bycatch of seabirds. Key to the collaboration was a long-term study into the effectiveness of various mitigation measures, and particularly the development of the integrated weight longline. This new line contains 50 grams of lead at its core, which makes it much heavier than standard longlines. The result is that this line sinks faster when set and arrives much quicker than standard lines at depths that are beyond the reach of most seabirds, especially albatrosses (Figure A).[224] The commission adopted the sink rate of 0.3 metres per second as one of its conservation measures.[221] That means this sink rate is part of the licence conditions that commercial fishers must adhere to in their operations.

Integrated weight longlines were readily adopted by owners of fishing vessels because these lines are part of the fishing gear and do not require extra effort to operate. They are now used widely in the world's longline fisheries and have reduced the mortality of white-chinned petrels by 95%.[225]

Box 7.8 *continued*

However, the problem remains for small petrels, like grey petrels, in some fisheries. These small seabirds can dive to depths of about 70 metres, making it very difficult to deter them, because they can quickly follow even a fast-sinking longline. Hence, another project was launched to develop an underwater-setting device that deploys baited hooks well below the ocean's surface where the petrels can neither see nor smell the bait. The bait setter uses a capsule that carries baited hooks 8–10 metres below the ocean's surface and is designed for tuna and swordfish in longline fisheries. Trials of a prototype of the device are currently under way.

The underwater bait setter delivers hooks 8–10 metres underwater, which are unseen by seabirds, and has the potential to eliminate the mortality of albatrosses and greatly reduce the mortality of deep-diving species, such as white-chinned petrels and shearwaters (photo by Graham Robertson, Australian Antarctic Division)

Petrels and albatrosses following a commercial fishing trawler, Southern Ocean
Photo by Nicolas Gasco

7.14 Assessment summary

Effectiveness of Antarctic environmental management

Summary	Assessment grade: Ineffective	Partially effective	Effective	Very effective	Confidence: In grade	In trend
World Heritage and protected areas						
Understanding: The nomination of World Heritage and protected areas is based on their recognised natural and cultural values				—	●	●
Planning: Management plans are in place and are reviewed regularly				—	●	●
Inputs: Financial, human and information resources are available to implement the management plans			—		●	●
Processes: For Heard Island and McDonald Islands, there is stakeholder consultation and all management plans are open to public consultation			—		●	●
Outputs and outcomes: Identified natural and cultural heritage values are being preserved			—		●	●
Land use and management						
Understanding: There is a good understanding of the impacts of human activities in our operational environment			—		●	●
Planning: The AAD's environmental management policy provides an overarching policy framework for all activities in the Australian Antarctic Territory and subantarctic islands. This policy is consistent with Australia's obligations under the Antarctic Treaty			↗		●	●
Inputs: The AAD administers an environmental management system supported by a program of scientific research			↗		●	●
Processes: The environmental management system is certified to the internationally recognised standard (AS/NZS ISO 14001:2004). The AAD's environmental policy was last reviewed in 2009			↗		●	●
Outputs and outcomes: Relevant management information collected through the environmental management system is used to guide management decisions			↗		●	●

Summary	Assessment grade (Ineffective / Partially effective / Effective / Very effective)	Recent trend	Confidence in grade	Confidence in trend
Adaptation to climate variability and change				
Understanding: There are several significant uncertainties about the impacts of climate change; however, scientific programs are in place to further our understanding of processes and future implications	Partially effective	Improving	Limited evidence or limited consensus	Limited evidence or limited consensus
Planning: The forecast infrastructure plan takes into account energy efficiencies and carbon emissions	Partially effective	Improving	Limited evidence or limited consensus	Limited evidence or limited consensus
Inputs: Adaptive management is resourced within the current operational framework	Partially effective	Improving	Limited evidence or limited consensus	Limited evidence or limited consensus
Processes: Scientific studies are examining potential effects of climate change	Effective	Improving	Limited evidence or limited consensus	Limited evidence or limited consensus
Outputs and outcomes: As scientific results become available, policies will be formulated	Effective	Improving	Limited evidence or limited consensus	Limited evidence or limited consensus
Pests and invasive species management				
Understanding: There is a good understanding of threats and impacts of alien species, both on the Antarctic continent and subantarctic islands	Very effective	Improving	Adequate high-quality evidence and high level of consensus	Adequate high-quality evidence and high level of consensus
Planning: Policies are in place to minimise the risk and impact of alien introductions	Very effective	Improving	Adequate high-quality evidence and high level of consensus	Adequate high-quality evidence and high level of consensus
Inputs: Human resources are allocated to implement policies that minimise the risk of alien introductions (participation in the Committee for Environmental Protection's Aliens in Antarctica science program, environmental officers on all stations, ships and at the AAD)	Effective	Stable	Adequate high-quality evidence and high level of consensus	Adequate high-quality evidence and high level of consensus
Processes: Environmental training and information are provided to all personnel and to the public	Effective	Improving	Adequate high-quality evidence and high level of consensus	Adequate high-quality evidence and high level of consensus
Outputs and outcomes: There is a legacy of alien introductions into Antarctic and subantarctic environments (e.g. rabbits and rodents on Macquarie Island); however, in recent years, programs have been effective in mitigating the risks	Effective	Improving	Adequate high-quality evidence and high level of consensus	Adequate high-quality evidence and high level of consensus

Recent trends: Improving; Stable; Deteriorating; Unclear

Confidence: Adequate high-quality evidence and high level of consensus; Limited evidence or limited consensus; Evidence and consensus too low to make an assessment

Grades: Very effective; Effective; Partially effective; Ineffective

AAD = Australian Antarctic Division

5

Resilience of the Antarctic environment

To date, the question of the level of resilience inherent in Antarctic ecosystems has not received much attention because it is a complex concept and many parameters required to assess resilience are still unknown. The Scientific Committee on Antarctic Research produced a comprehensive review of the impact of climate change on the Antarctic environment in 2009, highlighting areas where knowledge is still lacking. Although marine and terrestrial ecosystems are now better understood than in the past, baseline data on biogeography and biodiversity are still scarce, as are fundamentally important long-term monitoring data.[37] Researchers have only just started to investigate how organisms adapt to current climate change, and how resistant and resilient organisms and systems are.

At a glance

Organisms living in Antarctica have evolved to cope with severe events. However, it is challenging to measure their level of resilience and to predict how future climate change will impact Antarctic ecosystems because our understanding of key parameters is still limited, and with it our ability to assess adaptability, and hence resilience, of organisms and ecosystems.

For many, if not most, vertebrate species, important aspects of the dynamics of populations are either largely unknown or have been studied only at a few sites. Without comprehensive insights into variables, such as age of first reproduction, survival of different age classes, fecundity and the extent of emigration and immigration into and out of populations, as well as the drivers that influence these variables, we are unable to make long-term predictions about the viability of species in a changing environment. A thorough understanding of the ecological framework in which organisms live is also important when considering their resilience. For example, a number of Antarctic organisms live at South Georgia where the summers are up to 3 °C warmer than on the Antarctic Peninsula. Thus, the vulnerability of species needs to be determined on the basis of their ecological circumstances.[37]

Natural disturbances are part of life in Antarctic ecosystems and the endemic species are generally capable of surviving shock events because they have evolved strategies that allow their populations to rebuild after mass mortalities. Longevity among seabirds, and the ability of plant seeds to survive for long periods and to disperse, are among those strategies.

Shock events that test the level of resilience of a system occur in Antarctica just as they do in other parts of the world, ranging from intense storms affecting large areas to more localised incidents, such as scouring of the benthic environment by drifting icebergs (see Section 2.3.1). As long as these shock events are rare, communities can recover. However, increases in the magnitude and frequency of such events, as well as the duration of serious disturbances, are likely to become major challenges to the resilience of benthic communities. The slowest growing species may never recover if the interval between disturbance events is too short to develop and grow into mature organisms, whereas populations of fast-growing species may benefit if the competition for space, for example, is reduced.

We know that populations of some species of whales, seals and penguins have suffered human-induced mortality rates that pushed these species to the brink of extinction. Once hunting ceased, a number of species recovered; some, like king penguins, in a spectacular manner.[226-227]

However, these recoveries took place in a world where environmental conditions were not exposed to the rapid change that is currently under way. Today, a number of environmental components are changing rapidly (increasing sea temperatures, ocean acidification, higher intensities of ultraviolet radiation, etc.). The changes are complex and not always unidirectional, and there is currently little evidence on how the various factors are going to interact. There is no doubt that some organisms will benefit from these changes in the short term, but it is difficult to predict the effect of rapid climate variations on ecosystems. Many species may be vulnerable because their capacity to adapt operates at a much slower rate than the changes currently observed (see Section 3.1.1).

In the physical sciences, researchers are only just beginning to understand feedback loops and processes in the physical environment. Long-term monitoring data are also lacking in fields such as glaciology—particularly with regard to understanding changes in the active layer of the Antarctic ice sheet, as well as permafrost.[37] The Scientific Committee on Antarctic Research recommends studies to further the understanding of the hydrological cycle and emphasises the need for improved estimates of the freshwater budget. Atmospheric sciences also need to address changes in the atmosphere's chemistry to improve the ability of models to predict the consequences of changes in ozone concentrations.[37]

Glaciologist (Martin Truffer) on the slopes of Brown Glacier, Heard Island
Photo by Doug Thost

6

Risks to the Antarctic environment

It is clear that Earth's polar regions are likely to be affected severely by changing climate conditions.[6] These changes represent the highest risk to the region, since they are unlikely to be mitigated by any management measures. The impacts of climate change on the Antarctic environment are detailed in Sections 2 and 3 of this chapter.

Population and economic growth are leading to other risks. Remaining fish stocks around the world are highly depleted and appear largely unable to recover. With a growing human population demanding a new source of protein, the pressure on the industry to catch krill is likely to increase. A rapidly expanding krill fishery will have a considerable environmental impact and is a risk, particularly if the fishery expands at a rate that outstrips the ability of CCAMLR to manage it. In the past, the fishing nations that are active in the Southern Ocean had never reached the catch limits set by CCAMLR. However, in the 2009–10 season, the fishery reached the 'trigger level' in one of the subareas in the South Atlantic and the fishery was closed for the first time. Newly developed technology has allowed the vessels to catch about 800 tonnes per day compared with about 400 tonnes landed by 'old style' vessels.[31] This advanced fishing technology has contributed to the rise in the krill catch to 210 000 tonnes in 2009–10 and high catch rates may force the krill fleet to expand into new areas to avoid exceeding the existing catch limits.

The consequences of krill fishing continuously operating at the catch levels set by CCAMLR are as yet unknown. The impact of environmental changes on the krill population, such as ocean acidification,[228] will also have to be taken into account in the process for calculating precautionary catch limits for Southern Ocean fisheries.

Acidification of the world's oceans is occurring due to several concurrent processes but there is still much uncertainty about how, for example, climate change affects these processes, such as the 'biological pump'. However, it is well established that levels of anthropogenic carbon dioxide are increasing in the atmosphere, transferring 1 million tons of carbon dioxide to the world's ocean per hour.[229]

At a glance

As in other regions, the key risks to the Antarctic environment are being brought about by human activities often far away, including global population and economic pressures, and the effects of climate change.

While management can mitigate many of the population and economic impacts, climate change will be the main and uncontrollable driver bringing about change.

For the Southern Ocean, the process of overturning circulation (where deep water upwells and releases carbon dioxide to the atmosphere; see Section 1.1) is particularly important. As the atmosphere warms, the warming of surface waters increases stratification and limits gas exchange of this upwelled water with the atmosphere. This in turn causes greater retention of carbon dioxide, allowing more time for respiration of organic matter by marine bacteria. All these processes increase acidification.[229] An increasing number of studies are highlighting diverse and sometimes unexpected consequences on marine ecosystems:

- The effects of ocean acidification on the availability of nutrients and the ability of organisms to deposit and maintain exoskeletons of calcium carbonate is compromised. With less calcium in their shells they are lighter and less likely to sink into deeper waters. This reduces the flux of organic material to the deep ocean (the 'biological pump') and increases the amount of carbon dioxide that is respired in the upper water column.[230] The overall effect of climate change on the biological pump is influenced by many competing pathways (e.g. photosynthesis, grazing, sinking and respiration); the outcome is currently uncertain but is likely to have severe biological impacts within decades and could dramatically affect the structure and function of marine ecosystems.[27,80,196-199] Such changes would have profound effects on ecosystem

Antarctic expeditioner (Greg Hodge) framed by a crevasse
Photo by Doug Thost

services, including the productivity of fisheries and the efficiency of the Southern Ocean sink for atmospheric carbon dioxide. These changes are most pronounced in the polar regions where the acidity of the water is changing twice as fast as in warmer, tropical and subtropical regions.

- Growth and survival of fish populations could become impaired in an acidifying ocean. Tropical fish larvae that were exposed to increased levels of carbon dioxide changed their behaviour in a manner that made them five to nine times more prone to predation. Such an increase in mortality can be detrimental to the long-term survival of fish populations.[231]
- A decrease in the ocean's pH may affect the absorption of sound in the ocean, making the oceans noisier.[229,232] Whether this will impact marine mammals—for example, in their ability to communicate—is currently unclear.

Human activities are increasing on the Antarctic continent. The human footprint on Antarctica is small compared with the total size of the continent; however, the impacts are not evenly spread. Human activity and associated impacts are concentrated around stations, and stations tend to be built on ice-free land close to the sea. This land is also important habitat for the plants and animals of Antarctica. In East Antarctica, most of the sites suitable for building stations are already occupied and one new station is under construction. Currently, 53 research stations house up to 4000 individuals during summer and 1000 during winter.[233]

Through the Madrid Protocol's indefinite ban on mining activities in the Antarctic Treaty area, the Antarctic region is presently largely immune to the growing global demand for mineral resources. The Madrid Protocol and the Convention on the Conservation of Antarctic Marine Living Resources have so far been quite successful in managing human activities and reducing the impact of the human presence in the Antarctic region. However, as Tin et al.[233] concluded when reviewing human impact on Antarctica, 'In the coming decades, the effectiveness of these regimes [the Madrid Protocol and the Convention on the Conservation of Antarctic Marine Living Resources] will be put to the test in the face of the continuing increase in intensity and diversity of human activities in Antarctica'.

7.15 Assessment summary

Current and emerging risks to the Antarctic environment

	Catastrophic	Major	Moderate	Minor	Insignificant
Almost certain	Sea level rise through melt and ocean warming Increased warming of atmosphere, leading to loss of ice cover and changes in sea ice seasonality	Reversal of ozone hole, reducing ultraviolet B radiation but increasing warming Stronger winds and shift in oceanic fronts bringing warm water toward the ice shelf, leading to increased destabilisation of the ice			
Likely	Changes in ecosystem structure Increased illegal fishing, leading to impacts both on targeted and dependent species, as well as bycatch Breakdown in food web productivity	Increased pollution (water and air) Increase in commercial fishing activities, leading to impacts on targeted and dependent species Lack of knowledge of interactions of processes, leading to poor management decisions Increases in numbers of alien species with subsequent effects on native species and communities Improved survival of pathogens with subsequent effects on native species and communities	More continental stations, intensifying pressures on local environments		

	Catastrophic	Major	Moderate	Minor	Insignificant
Possible	■ Loss of biodiversity ■ Loss of keystone species as their physiological limits are exceeded	■ More extreme weather events due to climate change	■ Growth of tourism and the consequent increase in environmental impact (highly dependent on oil prices)		
Unlikely	■ Collapse of the Antarctic Treaty System (in the foreseeable future)	■ Mineral exploitation, leading to disturbance or destruction of the environment ■ Increased noise levels in ocean due to acidification, potentially impacting the communications of marine mammals	■ Oil and gas exploration, potentially leading to disturbance or destruction of the environment		
Rare					

□ Not considered

7

Outlook for the Antarctic environment

To assess the future of Antarctica and the Southern Ocean, a global perspective is required. Despite Antarctica's remoteness from centres of human population, the pressures generated in the rest of the world impact on Antarctic and Southern Ocean ecosystems through the linkages provided by atmospheric and oceanic circulations. Although the rate has slightly decelerated, the human population is still increasing and is expected to reach 9.3 billion in 2050.[234] Increasing demands for raw materials and protein sources can only increase the possibility that, at some stage, people will look to Antarctica and the Southern Ocean, especially when resources reach their limits in other parts of the world.

The Scientific Committee on Antarctic Research has reviewed all available information on the impacts of climate change on Antarctica and the Southern Ocean, and provides a comprehensive synthesis of the future of the southern continent in its report, *Antarctic climate change and the environment*.[37] The report highlights that changes have been observed in the Antarctic environment and continued changes are expected in the climate and weather patterns of Antarctica, as well as in the physical and chemical properties of the Southern Ocean. While many of the underlying processes driving the changes are still not well understood, the processes that are changing the Antarctic environment appear to be well under way and are unlikely to be stopped in the immediate future.

At a glance

At the moment, Antarctica is still in a comparatively good condition. However, the pressures on the continent and the surrounding ocean are going to increase. For example, the extraction of marine resources will not only continue but will intensify in future. Most importantly, numerous climate change processes are now under way that are likely to alter the physical Antarctic environment in our lifetime. In turn, ecosystems and species populations will be affected. Organisms will either have to adapt or they will disappear. The most likely candidates to vanish are those that have adapted to narrow environmental limits, such as emperor penguins, and invertebrates that grow and develop slowly. New fisheries will open as species more adapted to warmer conditions than currently found in the Southern Ocean move south.

Climate change and the future of Antarctica remain topics of intense scientific research and debate as analysis of data is still hampered by uncertainties and in some areas data deficiencies. Climate change is unlikely to be linear and various regions will be impacted on different scales, as the dissimilar developments in East and West Antarctica already demonstrate. Despite all uncertainties, the risks associated with climate change are significant and deserve our full attention.

While important regional differences of a number of indicators vary markedly in their expression and intensity, the overall trend away from the status quo in the Antarctic system is similar throughout the region. Change in East Antarctica is currently occurring at a slower rate than in West Antarctica, but the trends are similar. However, there are indications that this will change in the future. The fourth report of the Intergovernmental Panel on Climate Change predicts that changes expected in Antarctica will include a warming of the Southern Ocean, a freshening of at least its upper water masses, and a strengthening of the southern annular mode (SAM), which influences wind patterns.[6] SAM is expected to strengthen and its storm tracks are likely to move south. The result is strengthening westerly winds and increasing insulation of Antarctica. This would limit the heat exchange between Antarctica and the tropics, and cool the southern continent. At the same time, the ozone hole (which currently has a relatively stable size and depth) may recover. Presently, the ozone hole buffers Antarctica from warming through a layer of clouds and may have led to an increase in sea ice extent over the past 30 years. Its recovery, which is expected in

A Campbell albatross (*Thalassarche impavida*) in flight, Macquarie Island
Photo by Nick Rains

the middle of the 21st century, is likely to increase the warming of Antarctica, especially in the east. This makes it highly likely that the extent of sea ice will shrink: a reduction of 2.6 million square kilometres (or 33%) in the annual sea ice area is forecast (although models are currently unable to predict changes on a regional scale).

Over the next decades, ocean acidification will become more pronounced in the cold Southern Ocean than in warmer regions, particularly if the production of anthropogenic carbon dioxide continues at its present rate. There is a limit to how much carbon dioxide can be absorbed by the Southern Ocean and, if carbon dioxide production is not reduced, the Southern Ocean may no longer act as a carbon dioxide sink. A similar effect will be achieved as the ocean warms, because warmer waters have a reduced capacity to act as a carbon dioxide sink than cold waters. Over the past two centuries, the hydrogen ion concentration of surface water has increased by 30% in the world's oceans, lowering the pH by 0.1 units. This rate is about 100 times higher than it has been in the past.[83] Given the amount of carbon dioxide already in the atmosphere, a reversal of ocean acidification is unlikely in our lifetime.[83]

In all likelihood, the distribution of species will change as those adapted to warmer climes expand their ranges south. Those organisms already existing in the high Antarctic will have to adapt or they will disappear. The most likely candidates to vanish in the long term are those that have adapted to live in very narrow environmental limits. Their extended life histories mean that, with the increasing rate of change in their environment, fewer and fewer generations will be able to acclimatise and adapt to the new conditions. Range expansions have already been reported from the Antarctic Peninsula region. Some animal, plant and microorganism populations are expected to expand in areas where more liquid water will become available and temperatures will increase.

We cannot yet predict the extent to which biodiversity will be impacted by the expected future changes. However, ocean acidification in particular is likely to have a profound effect on the Antarctic ecosystem because it affects organisms at the base of the food web. Whatever changes may occur in the biodiversity of Antarctica, the effects are expected to cascade through the entire ecosystem.

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