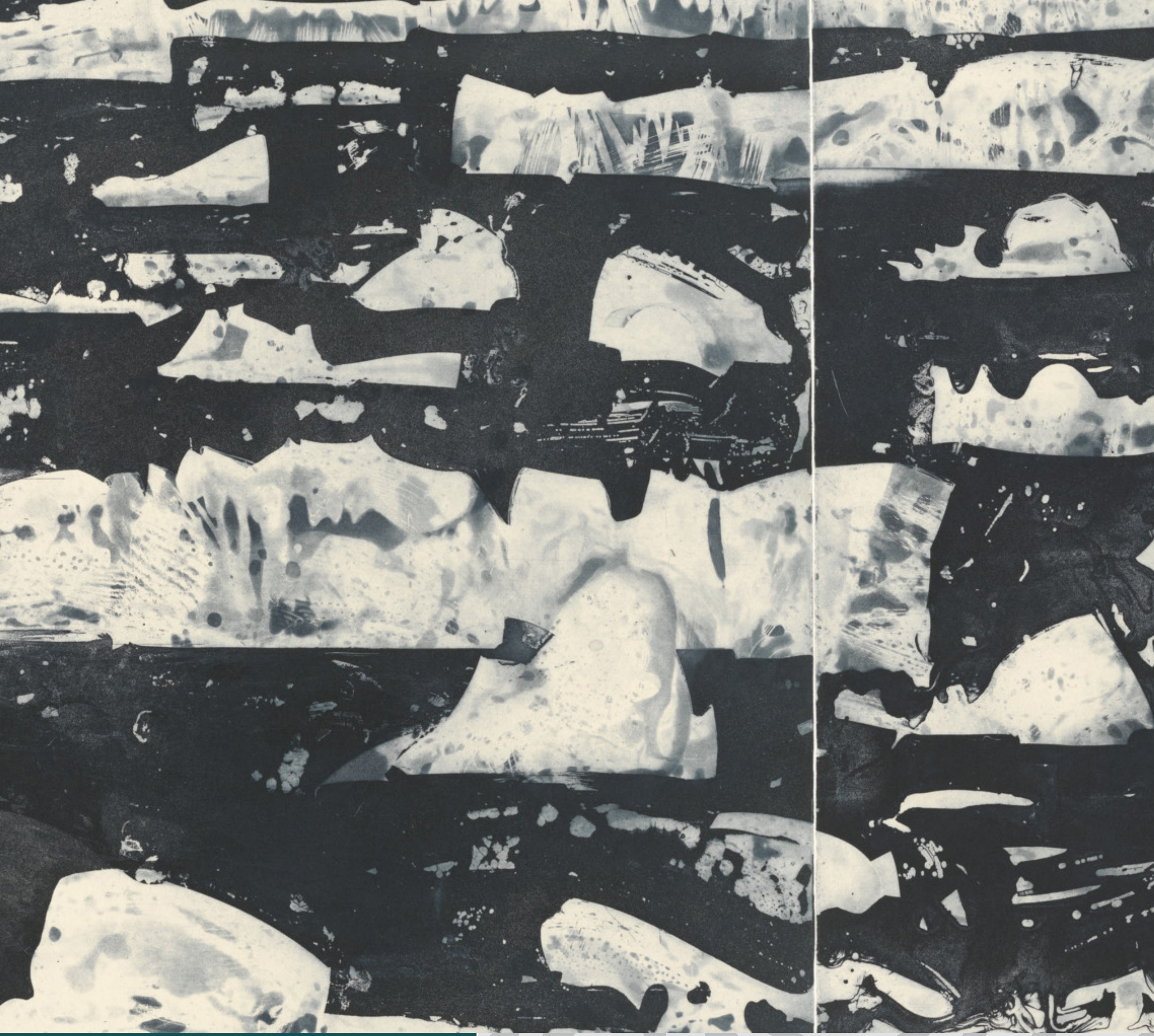

Antarctica

Australia
State of the Environment 2021

tunapri Palawa milangkani milaythina paywuta. tunapri muylatina muka-ti, nipakawa nuritinga kani pakana milaythina & muka liyanana Antarctica.

muka tina, pinungana & muta tapilti Antarctica-tu paywuta.

Nuyina, lukrapina lakarana, tapilti makuminya maytawinya-ta & yula; nara kipli muka-ti mapiya Antarctica.

liyanana panitha; muka ningina latu. warr! waranta pumili manina ngayapi, narakupa milaythina-nara-mapali & tina muka kitina, maytawinya lakarana.

manta manta.

Tasmanian Aboriginal knowledge comes from Country, and is connected to Country since the beginning of time. This knowledge embraces Sea Country, and the waters which carry our stories that connect us with the icy land and seas of Antarctica.

Marine animals, fish and birds migrate from northern lands to Antarctica and back, every year as they have done since creation.

The big ice-breaker Nuyina follows the path of the muttonbird and whale that feed in the waters around Antarctica.

But the ice is melting; ocean temperatures are rising! We must bring our planet back to life, care for our Country and the ocean's lifeworlds – from the smallest krill to the largest whale, for all the times to come.

Statement from the Tasmanian Aboriginal Centre, in palawa kani, the language of Tasmanian Aborigines.

Australia State of the Environment 2021

Antarctica

Barbara Wienecke
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Citation

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Disclaimer

Indigenous people should be aware that this publication may contain names and images of deceased persons.

Credits

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Acknowledgement of Country

The authors acknowledge the Traditional Owners of Country throughout Australia and their continuing connection to land, sea and community. We pay our respects to them and their cultures, and to their Elders both past and present.

Contents

Key findings

The Antarctic region is showing the effects of climate change

Antarctica, the Southern Ocean and subantarctic islands continue to show the effects of global climate change. The range and abundance of iconic species are changing; patterns in sea ice formation are increasingly unpredictable; and glaciers and ice sheets are melting. The Antarctic Peninsula and part of West Antarctica have experienced the greatest change. In East Antarctica, where Australia operates, the climate has remained comparatively stable over recent decades, although this conclusion is somewhat uncertain because detailed observations are lacking across much of this area.

The most important factors contributing to physical change in the Antarctic region are warming of the upper ocean and the lower atmosphere, caused by increasing emissions of greenhouse gases, and changes in atmospheric circulation, largely influenced by the cooling effect of ozone depletion during spring in the Antarctic stratosphere. The strengthening of near-surface winds over the Southern Ocean associated with ozone depletion has mitigated the influence of global climate change on the Antarctic region during summer.

Although the size of the Antarctic ozone hole varies from year to year, there is increasing evidence that stratospheric ozone concentrations are recovering. This is a direct result of the Montreal Protocol in successfully controlling the production and release of ozone-depleting gases. These controls are also helping to reduce the pace of global warming, because many of the human-made gases that cause ozone destruction are strong greenhouse gases.

Antarctica and the Southern Ocean affect the global climate and food webs

The Southern Ocean has continued to warm, and this has influenced the transport of heat and moisture in the margins of Antarctica. Major regional changes continue to occur in sea ice cover around the continent. The trend of increasing sea ice coverage from the 1980s appeared to be reversing in the 2010s. Changes in sea ice growth and retreat will change important oceanic circulation patterns that affect global climate and ecosystems. Overall, the contribution to global sea level rise from the melting of the Antarctic ice sheet and associated glaciers is becoming more important.

The Southern Ocean continues to absorb carbon dioxide (CO_2) from the atmosphere and is becoming more acidic (less alkaline) as a direct result. Ocean acidification, changes in wind strength, variability in sea ice and changes in the circulation of the Southern Ocean are affecting Antarctic ecosystems. Ocean acidification, in particular, is likely to have a profound effect on the Antarctic environment because it affects organisms at the base of the food web. Effects are likely to cascade through the entire ecosystem. However, our understanding of the responses by many Southern Ocean biota is relatively poor, making predictions of longer-term impacts highly uncertain. Changes in sea ice conditions affect the ability of animals that depend on the sea ice, such as penguins and seals, to breed successfully. Changes in sea ice extent and duration also affect populations of prey of Antarctic predators.

Changes are outpacing the ability of species to adapt, and some species will become extinct

The rate at which the physical environment of the Antarctic region is changing appears to be faster than the rate at which organisms, especially those of a higher order (e.g. fish, birds), can adapt to the changes. Although a few species may see benefits from some changes (e.g. more breeding territory may become available as glaciers retreat), these and other species may lose their prey resources, may be outcompeted by species that can adapt to the changing ecosystems, or may be replaced by species whose range is now extending from warmer climes into the Antarctic region. The candidates most likely to become extinct are those that have adapted to live within very narrow environmental limits.

Subantarctic islands are particularly at risk of invasions by non-native flora and fauna. Increasing temperatures allow more plant species to establish and may potentially enhance plant growth. At Heard Island, retreating glaciers may generate new habitat for both fauna and flora. Non-native microorganisms and invertebrates may also become established. Change is difficult to assess as visits to the island occur infrequently.

Fishing and other human activities add to the pressures on the Antarctic environment, and international collaboration is needed to better protect and manage the region

Commercial fisheries are a major human activity in the Southern Ocean. Fishing pressure may compound the pressures experienced by Antarctic fish from rising ocean temperatures, southerly shifts of frontal systems, and changes to sea ice extent and duration. The potential for cold-adapted fish to be resilient to the pressures is probably limited; new fisheries may rely on fish from warmer areas moving south.

Other human activities are increasing in the Antarctic environment, putting pressure particularly on the small ice-free areas. Disturbance, introductions of non-native species or disease vectors, and contamination – for example, with pollutants and plastics – can threaten local species and ecosystems.

Australia and other Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) members continue to advocate for the establishment of a representative system of marine protected areas in the Southern Ocean, including in East Antarctica and the Weddell Sea, and seek their endorsement by CCAMLR.

Outlook and impacts

Outlook

Currently, the Antarctic environment is still in comparatively good condition. However, the pressures on the continent and the surrounding ocean are increasing. For example, the influence of ocean warming on the melting of ice shelves and the coastal margins of the ice sheet is accelerating, human presence in the region is increasing, and extraction of marine resources is intensifying.

Most importantly, climate change processes are now underway that are likely to alter the physical Antarctic environment over the next decades to centuries, and are likely to become irreversible without policy interventions and technological advances. These changes will affect ecosystems and species populations. Organisms must adapt or will disappear. The candidates most likely to vanish are those, such as emperor penguins, that have adapted to narrow environmental limits, and species that grow and develop slowly, or have limited capacity to disperse. Species more adapted to warmer conditions and historically not found in the Southern Ocean are moving south, and may displace subantarctic and Antarctic species through competition for food or breeding habitat.

Climate change poses the most serious threat to Antarctic ecosystems. It requires an international effort to counteract its impacts and substantial financial investments to implement global strategies. The Antarctic Treaty System regulates human activities in Antarctica. Several organisations guide and provide advice on activities in Antarctica and the Southern Ocean. One of these is the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which seeks to conserve Antarctic marine living resources, including through the management of fishing activities in the Southern Ocean. Various international agreements are also in place, such as the Agreement on the Conservation of Albatrosses and Petrels, which sets guidelines for seabird-safe fishing practices.

Various efforts are underway to mitigate the impacts of other human-induced pressures. In Antarctica, the Antarctic Treaty parties recently adopted recommendations to reduce plastic pollution in Antarctica and the Southern Ocean (ATS 2021).

The great southern region – Antarctica and the Southern Ocean – is unique in the manner it has been managed through the Antarctic Treaty System. Given the new challenges Antarctica now faces – climate change, and increasing and diversifying human activities – Australia and other treaty nations are continuing to develop new regulatory instruments to ensure the continued protection of the Antarctic region and peaceful collaboration among nations.

Impacts

Changes are occurring in the climate and weather patterns of Antarctica, as well as in the physical and chemical properties of the Southern Ocean (WMO 2018, IPCC in press-a). Many climatic processes that are changing the Antarctic environment appear to be well underway and are likely to persist for decades or more. Although the physical basis of processes driving the changes is well understood, the precise details of the magnitude and rate of change, and the interactions of change processes across the physical and biological environment are the subject of ongoing investigation (Pecl et al. 2017, IPCC in press-b). The impacts of these changes include altered patterns of temperature, wind and precipitation across the Southern Hemisphere; the increasing contribution of Antarctica to global sea level rise; and effects on the global oceans of changes in the state of the Southern Ocean.

Impacts on ecosystems

Increasing uptake of carbon dioxide (CO_2) into the ocean is causing ocean acidification that is likely to have severe biological impacts within decades. The impacts on the structure and function of marine ecosystems could be dramatic (Feely et al. 2004, Doney et al. 2009, Hutchins et al. 2009, Orr et al. 2009, Dupont et al. 2010, Ericson et al. 2010, Hancock et al. 2020, IPCC in press-a). Such changes would have profound effects on ecosystem services, including the productivity of fisheries, and the ability of the Southern Ocean to absorb and store greenhouse gases. These changes are most pronounced in the Southern Ocean because of the naturally low levels of calcium carbonate (CaCO3) and the greater solubility of CO_2 in cold water (Figuerola et al. 2021).

Impacts on krill and fish stocks

The demand for krill oil tablets as a dietary supplement and for fishmeal is currently driving an increase in krill catches (Cavanagh et al. 2021), although krill is rarely consumed directly by humans (Nicol & Foster 2016). Furthermore, the value of toothfish has increased over recent years, which could increase the incentive for illegal, unreported and unregulated fishing.

The ecosystem consequences of krill fishing continuously operating at the catch levels set by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) are unknown, but these catch levels currently appear to be sustainable and consistent with the maintenance of krill-dependent predators. However, there is a long-term trend for the fishery to concentrate catches in a few small areas, which may lead to localised depletion and impacts on krill-dependent predators (Watters et al. 2020). CCAMLR has adopted conservation measures that seek to spread krill catches over a wider area. However, a more comprehensive management regime is required to better ensure that the needs of predator species are taken into account. The impact of environmental changes such as ocean acidification on krill populations (Kawaguchi et al. 2009) will also have to be considered when setting catch limits for Southern Ocean fisheries.

Impacts on global food production

The flow-on effects of altered climate patterns in the Antarctic and Southern Ocean region include changing precipitation patterns in the mid-latitudes of the Southern Hemisphere, with consequences for the resilience of food production and ecosystems (IPCC 2013). The impact of climate change on food production is already becoming apparent and varies regionally. Whereas crop yields have generally increased in South America, the impact has been negative in other areas. For example, in Australia, the production of wheat decreased by around 9% per year from 1974 to 2013 (Ray et al. 2019).

Impacts on aesthetic and wilderness values

The Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol), adopted in 1991, came into force in 1998. Article 3 of the protocol declares the ‘protection of the Antarctic environment and dependent and associated ecosystems and the intrinsic value of Antarctica, including its wilderness and aesthetic value ... shall be fundamental considerations in the planning and conduct of all activities in the Antarctic Treaty area’. Under Annex V of the protocol, some areas are designated Antarctic Specially Protected Areas to manage and ‘protect outstanding environmental, scientific, historic, aesthetic or wilderness values’ (Secretariat of the Antarctic Treaty 2021).

Increasing human activities and expansion of the areas accessed by humans may put aesthetic and wilderness values at risk. Issues yet to be resolved are the absence of assessment methods and lack of an agreed definition of these values (Summerson & Bishop 2012, Leihy et al. 2020).

Impacts on human health and wellbeing

The Antarctic region is widely regarded as being of special significance to society because of its central role in the climate system, its importance in oceanic food production, and its wilderness and aesthetic values. Although humans derive various benefits from Antarctica and the Southern Ocean, the climate and ecosystem services they provide are still largely underappreciated. A recognition of the values, the manner in which they are linked and the feedback mechanisms at play may improve future management of the region (Bax et al. 2021, Cavanagh et al. 2021).

Assessment Social wellbeing related to Antarctica

2021

Adequate confidence

The environment of Antarctica is changing, and this will affect global climate and marine systems, with flow-on effects to human wellbeing.

Assessment Health of the planet

2021

Adequate confidence

The environment of Antarctica is changing, and there are increasing pressures on the ecosystem from variability and trends in weather and climate patterns, and the state of the ocean.

Assessment Positive environmental stewardship and international cooperation

2021

Adequate confidence

Nations continue to work cooperatively to protect the Antarctic environment.

Assessment Protection of key species

2021

Adequate confidence

There are encouraging signs that some key species that have been under threat are recovering. However, the populations of some species are still decreasing.

Assessment Ecosystem services

2021

Adequate confidence

Benefits humans derive from Antarctic ecosystems include food provision, carbon capture, nutrient cycling, research, aesthetic experiences, tourism and recreation.

Assessment ratings

For assessments in the 'Outlook and impacts' section

- **Very good**: The environment is in very good condition, resulting in enhanced environmental values.
- **Good:** The environment is in good condition, resulting in stable environmental values.
- **Poor:** The environment is in poor condition, and environmental values are somewhat or slowly declining.
- **Very poor:** The environment is in very poor condition, and environmental values are substantially and/or rapidly declining.

Trend

- ↗ **Improving:** The situation has improved since the previous assessment (2016 state of the environment report).
- — **Stable:** The situation has been stable since the previous assessment.
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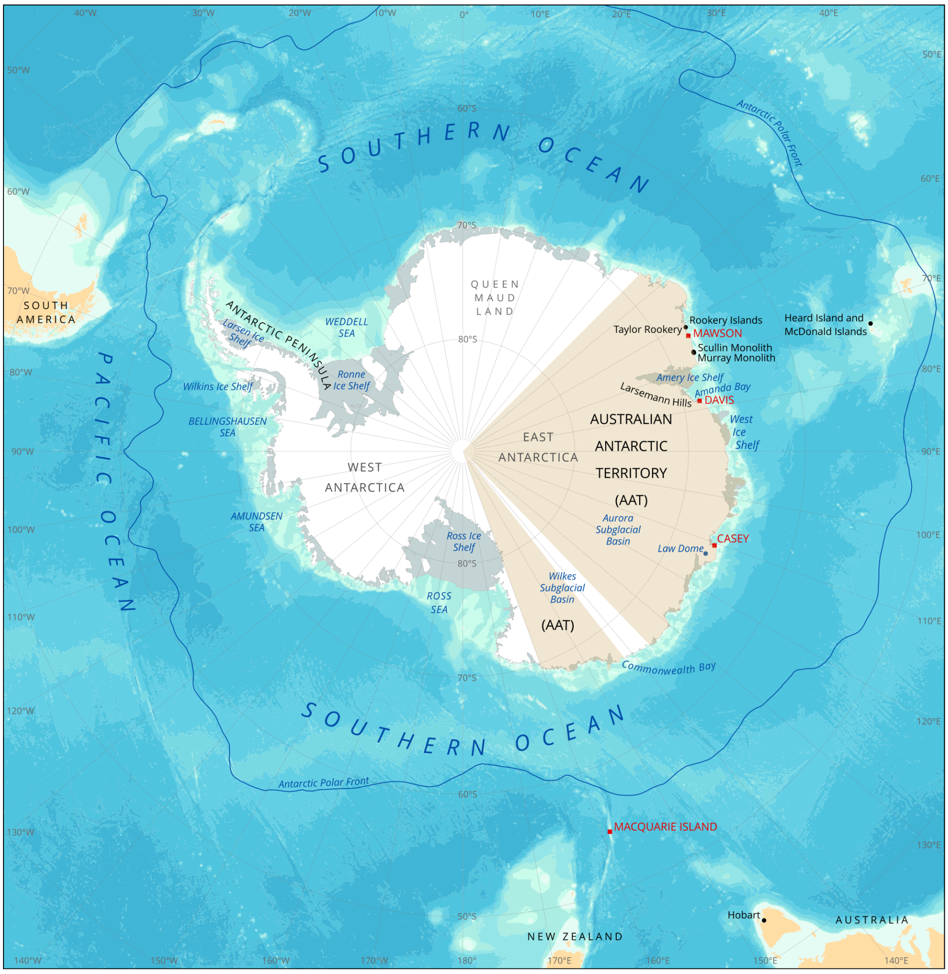
Environment

Physical environment

This report focuses mainly on the environment of areas administered by Australia (the Australian Antarctic Territory – AAT – and the Territory of Heard Island and McDonald Islands), subantarctic Macquarie Island (which is part of Tasmania) and the Southern Ocean adjacent to these areas (Figure 1). Macquarie Island is managed by the Tasmanian Government, while the wider Antarctic regions are managed cooperatively through the international agreements of the Antarctic Treaty System, in which Australia is a leading participant. Many aspects of Australia's interests in the region relate to the environment of broader geographical areas, which are described where required.



Source: Australian Antarctic Data Centre

Figure 1 Antarctica and the Australian Antarctic Territory

Antarctica is Earth's southernmost, coldest, highest, windiest and driest continent. Including all islands and ice shelves, it covers an area of about 14.2 million square kilometres (km^2) – nearly twice that of Australia.

Although isolated from other continents, Antarctica and the surrounding Southern Ocean are major drivers of global weather and climate (Owens & Zawar-Reza 2015). Interactions between the atmosphere, ice and ocean in the Antarctic region set up patterns of weather and climate that extend across the Southern Hemisphere and northward across the equator. These patterns interact with the land and ocean at lower latitudes, which in turn influences the southward flow of heat and moisture to affect the Antarctic continental margin and interior (Marshall 2007, Noble et al. 2020).

The weather and climate of Australia feel the influence of the Antarctic region because Australia is geographically close to the region, and is affected by mutual interactions with large-scale modes of climate variability (van Ommen & Morgan 2010, Vance et al. 2015, Lim et al. 2019, Abram et al. 2021, Udy et al. 2021). Consequently, understanding the state of the physical environment in the Antarctic region is important for assessing the state of the Australian environment.

Atmosphere

Atmospheric change in the Antarctic region can be divided into changes at and near the surface (primarily in temperature, wind and precipitation), and changes in the upper levels (primarily in ozone concentration, temperature and wind).

Surface changes

Patterns of change in the Antarctic surface climate have been mixed in recent decades (Hartmann et al. 2013, Turner et al. 2014, Meredith et al. in press).

Significant regional surface warming occurred in parts of the Antarctic Peninsula and the West Antarctic Ice Sheet from the late 1950s to the end of the 20th century (Turner et al. 2005b, Steig et al. 2009, Hartmann et al. 2013, Turner et al. 2014). The rate of this warming was among the most rapid anywhere on the globe (Steig et al. 2009, Bromwich et al. 2013).

Since the beginning of the 21st century, the Antarctic Peninsula has generally cooled (Turner et al. 2016), although an indication of warming from the mid-2010s has been reported (Carrasco et al. 2021). Warming in spring across the Antarctic Peninsula and West Antarctica over 1979–2012 was also observed (Clem & Fogt 2015). In East Antarctica, temperatures since the 1950s have generally shown no significant trends, apart from indications of weak cooling during autumn in the interior (Nicolas & Bromwich 2014, Jones et al. 2016). These changes have recently been confirmed by Turner et al. (2020a), who also found that the interannual variability on the western Antarctic Peninsula has decreased since the late 1950s as sea ice in the region has declined.

Turner et al. (2020a) have provided the most recent detailed analysis of temperature trends for Australia's 3 continental Antarctic stations. Over 1979–2018, no significant trend was found for Mawson and Davis, either annually or seasonally. For these stations, the 95% confidence limit for the annual trend is approximately 0.2 °C per decade. Over the same period, a statistically significant cooling at the 95% confidence limit was found for Casey, for the overall annual mean temperature (trend −0.26 ± 0.24 °C per decade) and for the winter mean (trend −0.58 ± 0.51 °C per decade). Similar trends over the modern observational record are indicated by BOM (2019). For Macquarie Island, similar analysis to that by Turner et al. (2020a) using data from BOM (2019) indicates that any trend in the annual mean temperature over 1979–2018 was not statistically significant (within the 95% confidence limit of 0.1 °C per decade). However, during this period, and indeed since around 1970, Macquarie Island has shown a marked increase in annual rainfall, particularly in winter.

The overall cause of climate shifts in the Antarctic region is likely to be a combination of variability due to the natural internal modes of climate variability, particularly the Southern Annular Mode (SAM) and the El Niño–Southern Oscillation (ENSO) and their interactions, and the influence of global climate change (IPCC 2013).

As noted in the 2016 state of the environment report, of particular significance for the climate of the Antarctic region has been the tendency of the SAM to shift towards a more positive state during summer in recent decades (Marshall 2003). A strengthening of the westerly wind belt over the Southern Ocean and a shift of its core towards Antarctica have accompanied this change, and caused warming of the Antarctic Peninsula and cooling in the interior of East Antarctica (Thompson & Solomon 2002, Gillett et al. 2006, Marshall 2007, McLandress et al. 2011, Polvani et al. 2011, Thompson et al. 2011). Previous observational and model studies have pointed to the springtime Antarctic ozone hole (see case study: The Antarctic ozone hole), which has been brought about by human-produced emissions of ozone-depleting substances, as the main driver of the summer shift in the SAM (see Upper-level changes). In the case of the cooling trend at Casey, this is largely consistent with the effect of the annual mean change in the SAM (Turner et al. 2020a). The lack of significant temperature trends at Mawson Station, Davis Station and Macquarie Island suggests that other climate processes are countering the effect of changes in the SAM.

Because of the relatively short length of the observational record and the inherent level of interannual climate variability for the Antarctic region, the Intergovernmental Panel on Climate Change (IPCC 2013) determined that only low confidence could be ascribed in linking greenhouse warming to the observed temperature changes in Antarctica. It is still unclear how the large-scale climate modes, including ENSO, are responding to anthropogenic (human) forcing (Hartmann et al. 2013) and affecting Antarctica. However, it is clear that natural climate variability that is unforced by human influences has played a role, together with the changes in the SAM, in recent patterns of climate variability in the Antarctic region (Turner et al. 2016, Smith & Polvani 2017).

Studies published since the 2016 state of the environment report have provided new insights into the causes of changes in the Antarctic atmosphere. Evidence continues to emerge that, since the turn of the 21st century, the ozone hole has been repairing as a result of the action of the Montreal Protocol (WMO 2018). This has led to a pause in surface wind changes over the Southern Ocean (Banerjee et al. 2020) associated with the summertime shift in the SAM (Fogt & Marshall 2020). Various studies have highlighted the influence of the tropical oceans on Antarctica. Turney et al. (2015) showed that specific regions of the southern mid-latitudes regulate the exchange of heat across the Southern Ocean. According to Clem et al. (2018), increases in the La Niña phase of ENSO have been responsible for cooler temperatures in western East Antarctica in the past 2 decades. Variability in the Pacific Ocean is also implicated as having an increasing influence on Antarctic surface temperatures (Rahaman et al. 2019). In addition, recent extremes in Antarctic temperatures have highlighted the large-scale climate connections that occur across the Southern Ocean.

New climate simulations have provided insights into possible future surface changes, and have shown that the effect of anthropogenic climate change is likely to increase. Bracegirdle et al. (2020) examined state-of-the-art climate simulations for 4 greenhouse gas emissions scenarios. Overall, they found increased surface temperatures and precipitation across the Antarctic continent for all future projections, with mitigating influences under low-emissions scenarios by heat and carbon dioxide (CO_2) uptake by the Southern Ocean, and by ozone recovery. Cai et al. (2021) examined the contributions to 'polar amplification', which is the increased warming of the polar regions associated with climate change, and found that, for the Antarctic region, the main contribution to warming occurs in winter due to uptake of heat by the global oceans.

Upper-level changes

The 2016 state of the environment report summarised the observational evidence for the overall cooling of the Antarctic upper atmosphere over recent decades. Subsequent studies have further characterised temperature changes in this region.

Ozone in the upper parts of the atmosphere absorbs solar energy and causes heating in the lower atmosphere and at Earth's surface. Consequently, trends in ozone have influenced temperature trends in the lower stratosphere (10–30 km altitude) during spring. During the growth of the ozone hole over 1979–97, the lower atmosphere cooled; as ozone concentrations have been recovering, it has warmed (Randel et al. 2017, Solomon et al. 2017).

In the upper stratosphere (30–50 km altitude) and mesosphere (50–95 km altitude), global temperatures have cooled over several decades (Randel et al. 2017). This is consistent with the increasing greenhouse gases in the lower atmosphere blocking more of Earth's heat before it reaches the upper levels of the atmosphere (Goessling & Bathiany 2016).

Above Australia's Davis Station, the temperature trend between 1995 and 2018 in the upper mesosphere (near 87 km altitude) was −1.2 ± 0.5 °C per decade after accounting for influences from the solar activity cycle (French et al. 2020a). Related work (French et al. 2020b) identified a previously unrecognised temperature modulation in the upper mesosphere with a period of approximately 4–5 years. The interaction of ocean and atmospheric modes of climate variability at lower altitudes appears to force this variability.

Case study The Antarctic ozone hole

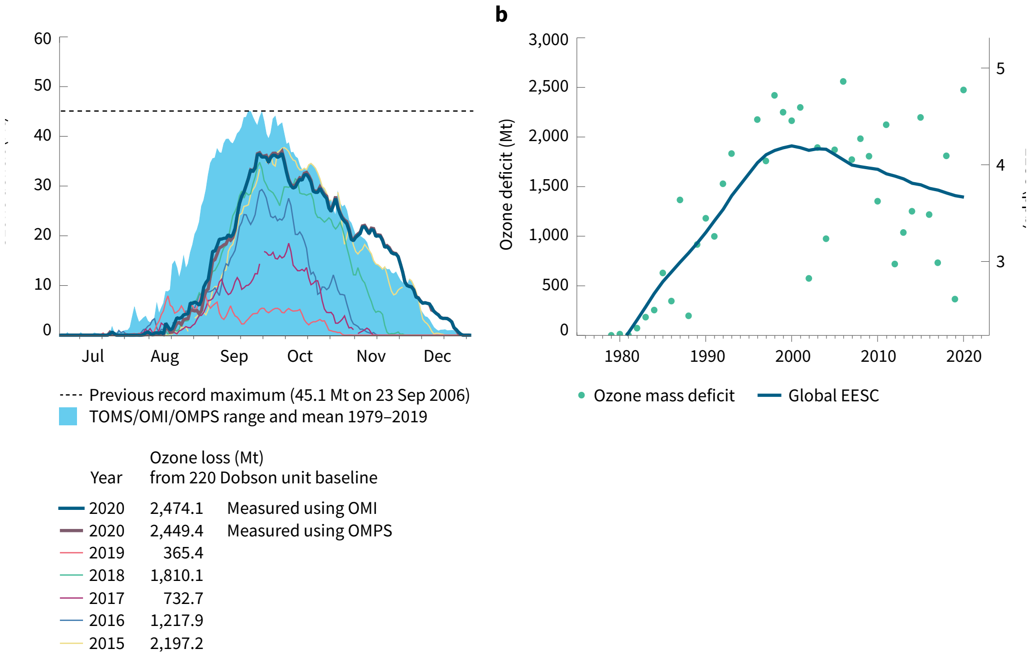
The 2016 state of the environment report found emerging indications of improvement in Antarctic stratospheric ozone concentrations. Measures of the size and depth of the Antarctic ozone hole generally indicate that ozone depletion started to become significant in the late 1970s, reached a peak between the late 1990s and early 2000s, and is currently improving towards recovery to 1980 levels in the mid-to-late 21st century (WMO 2018).

The latest comprehensive assessment of ozone depletion by the World Meteorological Organization and the United Nations Environment Programme found evidence of Antarctic ozone recovery, with international controls on ozone-depleting substances due to the Montreal Protocol having 'made a substantial contribution to the observed trends' (WMO 2018).

However, ozone depletion shows significant year-to-year variability, and in any particular year is more strongly influenced by meteorological factors than changes in the atmospheric concentrations of ozone-depleting substances (Solomon et al. 2015). In particular, the amount of ozone destruction is strongly related to the temperature of the Antarctic stratosphere during the winter and spring, with colder temperatures causing a larger ozone hole.

The severity of ozone depletion varies on seasonal and interannual timescales (Figure 2a). The largest observed measures of depletion generally occurred in 2006, and subsequent years have all shown less ozone loss. Tully et al. (2019) showed that ozone depletion decreased from 2001 to 2017, in line with the decline in the estimated atmospheric concentration of ozone-depleting substances (Figure 2b).

The year 2019 was notable in having the smallest Antarctic ozone hole since 1988 (Kramarova et al. 2020). This was mainly because of the strong and rapid warming of the Antarctic stratosphere that occurred during spring of that year (Klekociuk et al. 2021). The stratospheric warming was related to climate patterns that produced hot and dry conditions across Australia in the 2019–20 summer (Lim et al. 2020); see case study: Antarctic temperature extremes. In contrast, a large amount of Antarctic ozone destruction occurred in 2020, rivalling the total loss observed in 2006 (Figure 2b). In this case, low temperatures and relatively stable circulation in the Antarctic stratosphere were the main determining factors.



EESC = equivalent effective stratospheric chlorine; Mt = megatonne; OMI = Ozone Monitoring Instrument; OMPS = Ozone Mapping and Profiler Suite; ppb = parts per billion; TOMS = Total Ozone Mapping Spectrometer

(a) Estimated daily mass of ozone destroyed within the ozone hole, shown for individual years from 2015 to 2020 as a function of day of year from July to December. (b) Estimated total annual ozone mass loss associated with the ozone hole from 1979 to 2020 (green dots) and EESC (blue line), a measure of the stratospheric concentration of ozone-depleting substances. These figures are obtained from CSIRO analysis of daily total column ozone measurements provided from the OMPS on the Suomi National Polar-orbiting Partnership satellite. In (a), the light-blue background shows the range of daily values for 1979–2019 obtained with the TOMS instrument (1979–2003), the OMI (2004–11) and OMPS (2012–19). Gaps in the timeseries are when no TOMS measurements were made.

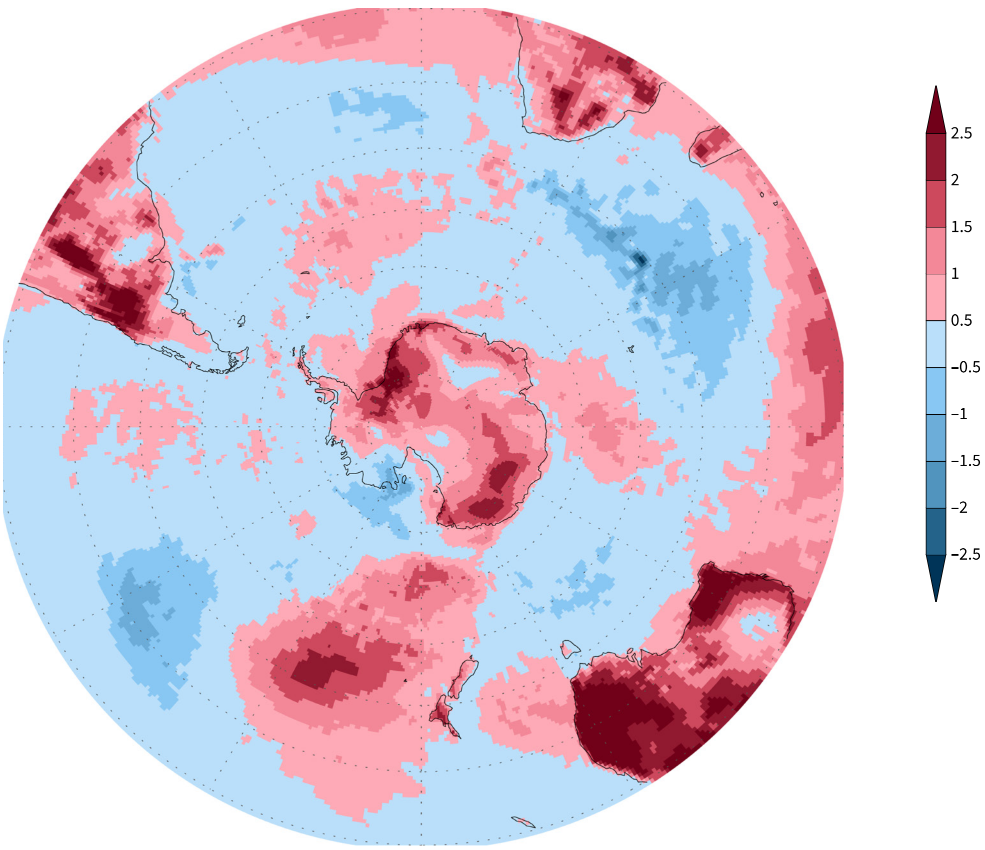
Source: CSIRO; after Klekociuk et al. (2021)

Figure 2 Ozone mass deficit metric

Case study Antarctic temperature extremes

During the 2019–20 summer, unprecedented maximum daily temperatures were observed in parts of coastal Antarctica (Robinson et al. 2020). The consequences of this event for the ice-free areas of Antarctica are of concern, as these regions are key oases of biodiversity where plants and animals have adapted over millennia to a specific narrow range of physical conditions, particularly in terms of air and surface temperature, and low and highly seasonal availability of water. By increasing the availability of water, warmer conditions may benefit certain Antarctic organisms that are drought stressed (particularly in terms of growth and reproduction). However, excessive or prolonged exposure to temperatures well above zero can lead to detrimental effects such as heat stress, increased likelihood of community dislocation from flooding, and potential for future drought stress when local water reserves are disrupted.

A persistent pattern of above-average temperatures that began in East Antarctica during the spring and generally moved eastwards, arriving in the Antarctic Peninsula region by late summer, caused the extreme temperatures (Figure 3). An important trigger for these unusual conditions was the strongly negative phase of the Southern Annular Mode (SAM) during most of spring and summer, with southward movement of warm air masses across the Southern Ocean. The state of the SAM was supported by El Niño conditions in the Pacific Ocean, and by the positive phase of the Indian Ocean Dipole (Lim et al. 2020). Tropical surface conditions also aided the strong warming of the Antarctic stratosphere during spring, and may have influenced Antarctic surface temperatures during the summer.



Note: Shown are differences in the maximum daily temperature averaged over November and December 2019 with respect to the climatological average for 1980–2010. The scale is degrees Celsius.
Source: After Robinson et al. (2020). Royal Netherlands Meteorological Institute Climate Explorer using data from the European Centre for Medium-range Weather Forecasts, fifth Reanalysis.

Figure 3 Patterns of average maximum temperatures across the Southern Hemisphere in November–December 2019

Assessment State and trends of the Antarctic atmosphere

2021

Adequate confidence

The Antarctic atmosphere is generally poor and deteriorating, with increases in temperatures and increasing greenhouse gas concentrations.

Assessment Surface temperature

2021 **2016** **2011**

Adequate confidence

Annual average temperatures have generally increased throughout Antarctica since 1957, with the most marked warming occurring in the Antarctic Peninsula region and West Antarctica.

Assessment Upper atmosphere temperature (upper troposphere to mesopause)

2021 **2016** **2011**

Adequate confidence

Despite signs of recovery in ozone, there is a general cooling trend, due mainly to the effect of increasing greenhouse gas concentrations.

Assessment Stratospheric ozone concentration

Adequate confidence

There are signs of recovery (increased concentration of ozone) in spring and summer above Antarctica, but there is also significant interannual variability because of meteorological factors. Stronger signs of ozone recovery are expected during coming years.

Assessment ratings

For assessments in the 'Environment' section

- **Very good**: The environment is in very good condition, resulting in enhanced environmental values.
- **Good:** The environment is in good condition, resulting in stable environmental values.
- **Poor:** The environment is in poor condition, and environmental values are somewhat or slowly declining.
- **Very poor:** The environment is in very poor condition, and environmental values are substantially and/or rapidly declining.

Trend

- **Improving:** The situation has improved since the previous assessment (2016 state of the environment report).
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Cryosphere

The cryosphere comprises the parts of Earth that have frozen water in the form of snow and ice, including sea ice, glaciers, ice sheets and icebergs. About 90% of Earth's ice occurs in Antarctica. With a volume of approximately 26.9 million km^3 (Fretwell et al. 2013), the Antarctic ice sheet contains 70% of the world's fresh water. If it melted, sea levels would rise by 58 m (Fretwell et al. 2013, Vaughan et al. 2013).

The annual growth and retreat of the Antarctic sea ice represents one of nature's most significant large-scale annual changes. Sea ice forms when the temperature of the ocean surface decreases below approximately −1.8 °C. At its maximum annual extent in September–October, Antarctic sea ice covers a total area of up to 20 million km^2 (Fretwell et al. 2013), which retreats to a minimum area of about 3 million km^2 in February (Parkinson 2019). This annual cycle and the associated processes of sea ice formation and melt are of immense importance for weather, climate, ecosystems and human activities.

The Antarctic continental ice also provides a wealth of information about past climate. The ice forms from atmospheric moisture, which reaches the surface in the form of snow and small ice particles called 'diamond dust' (Grieger et al. 2016, Thomas et al. 2017). This material, along with trapped air, provides a detailed record of past climate (see case study: Antarctic ice-core records of past climate and atmospheric composition). The ice also preserves dust of continental and extraterrestrial origin, and other transported particulates such as sea salt.

As interpreted from the marine sediment record, the complete glaciation of Antarctica began about 34 million years ago. This was triggered by a decline in CO_2 levels to below 600 parts per million (DeConto & Pollard 2003, Galeotti et al. 2016). The ongoing glaciation was reinforced when Antarctica became fully surrounded by ocean about 30 million years ago (Noble et al. 2020).

Case study Antarctic ice-core records of past climate and atmospheric composition

Ice-core CO_2 records

The oldest ice-core record obtained from Antarctica, the EPICA Dome C record, reaches back 800,000 years (Lüthi et al. 2008, Bereiter et al. 2015). Temperature reconstructions, which are based on the correlation of stable isotope concentration ratios (primarily $^{18}O/^{16}O$ and $^{2}H/^{1}H$; O = oxygen and H = hydrogen) with temperature, and concentration measurements of CO_2 and other stable gases in this and other deep ice cores, provide unique insight into the climate system. The data demonstrate the close coupling that has existed over millennia between the carbon cycle and Earth's climate. This provides the clearest known evidence that changes in atmospheric CO_2 accompanied and contributed to the ice age cycles that dominated climate, sea level and ice-sheet variability over this interval.

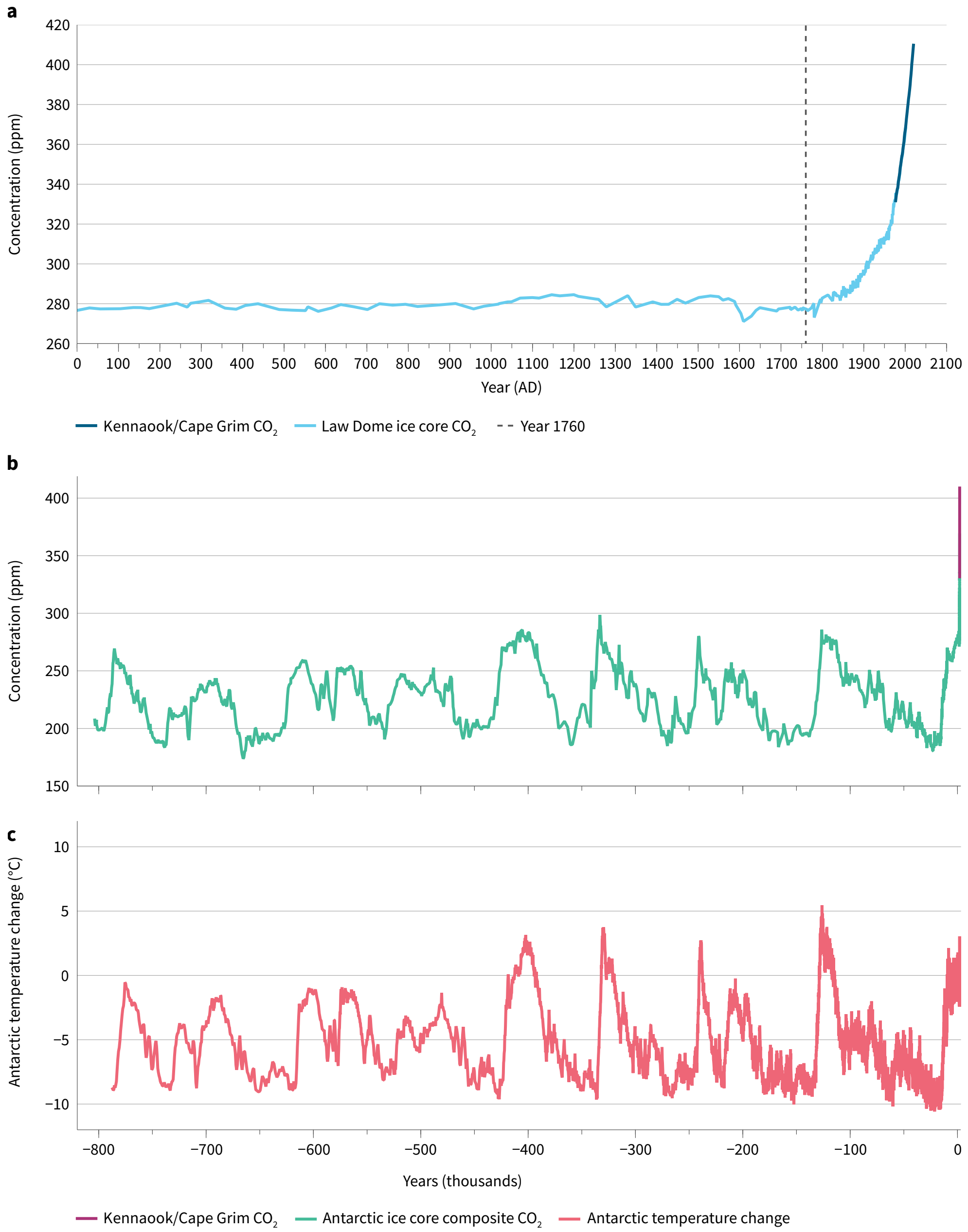
The Law Dome ice-core record, drilled to bedrock around 100 km inland from Australia's Casey Station, provides the world's most detailed CO_2 record of the past 2,000 years (Figure 4a). The Law Dome data show that atmospheric CO_2 concentrations have increased by close to 50% (from 280 to 417 parts per million) since the start of the Industrial Revolution; they are now higher and accelerating faster than at any time during the past 800,000 years (Figure 4b). Furthermore, studies of the changing isotopic composition of CO_2 in the Law Dome and other Antarctic ice cores reveal unequivocally that the primary origin of this CO_2 increase is the burning of fossil fuels (Rubino et al. 2013).

Ice cores and past climate variability in Australia

Analysis of ice cores can also show the changes in the chemical composition and accumulation rates of snow on the Antarctic ice sheet over time. At ice-core sites such as Law Dome near Casey Station, the chemistry and accumulation rates have been reconstructed at subannual resolution over the past few thousand years (Roberts et al. 2015). Trends and natural variability in these parameters shed light on past environmental conditions in Antarctica, and on conditions in the surrounding oceans and continents. Two examples of connection established between the ice-core data and the Australian climate follow.

Since the late 1960s, south-west Western Australia has been subject to an extended drought, with a decline in winter rainfall of around 20% that has had a major impact on regional agriculture. Comparison of Australian rainfall data with snowfall at Law Dome, as measured from ice cores, reveals that high snowfall accumulation at Law Dome is associated with atmospheric circulation patterns that bring dry conditions in south-west Western Australia. Based on this correlation, the long-term ice-core record can be used to evaluate whether the present drought is unusual. It shows that the recent amount of snowfall accumulation at Law Dome is the largest it has been in the past 1,200 years; comparable but smaller events occurred around 400 AD and 750 AD (van Ommen & Morgan 2010).

Eastern Australia is also subject to large rainfall variability on annual to multi-decadal timescales, including the millennium drought between 1995 and 2009. The El Niño–Southern Oscillation, which strongly affects rainfall in eastern Australia, also affects winds around Antarctica, which in turn influence the chemical (sodium ion) composition of the snow at the Law Dome ice-core site. This link has been used to reconstruct past rainfall in key eastern Australian catchments. Results show that the short period of modern rainfall observations is not representative of the full range of past climate variability, and that droughts worse than the millennium drought are not only possible but likely (Vance et al. 2015).



CO_2 = carbon dioxide; ppm = parts per million
(a) Law Dome ice-core CO_2 record, the world's most accurate and detailed CO_2 record for the past 2,000 years. Note the clear increase in CO_2 from the start of the Industrial Revolution and the agreement of the ice-core measurements with more recent atmospheric data from Kennaook/Cape Grim, Tasmania. (b) Data from a composite of Antarctic deep ice cores reveals past changes in Antarctic (b) CO_2 and (c) temperature over the past 800,000 years. The modern rise is outside the bounds of natural variability over this period. Note the close coupling of temperature and CO_2 throughout the ice age cycles, which have approximately a 100,000-year periodicity.
Sources: Kennaook/Cape Grim CO_2 – Kennaook/Cape Grim Baseline Air Pollution Station (Australian Bureau of Meteorology, and CSIRO Oceans and Atmosphere); Law Dome CO_2 – MacFarling Meure et al. (2006); Antarctic ice-core composite CO_2 – Bereiter et al. (2015); Antarctic temperature change – Jouzel et al. (2007).

Figure 4 History of climate and atmospheric composition from Antarctic ice-core records

Antarctic ice sheet and glaciers

Melting of the Antarctic ice sheet and the icebergs it discharges adds freshwater to the Southern Ocean (Hammond & Jones 2016). The amount of melting has increased since the 1990s (Rignot et al. 2019), escalating Antarctica's contribution to global sea level rise. Changes in the salinity of the Southern Ocean because of freshwater input have affected its structure and circulation, the availability of iron for ocean ecosystems, and the timing and extent of sea ice production (Bintanja et al. 2013, Meredith et al. in press). The effect of these influences on a variety of Antarctic taxa, such as krill, seals and penguins, is not well understood.

Overall changes to the ice sheet and glaciers

The Antarctic ice sheet gains mass by snow and ice deposition, and loses mass by the discharge of melt from ice shelves, basal ice and surface run-off; the sublimation of surface ice; and the formation (discharge) of icebergs at the coast.

There are 3 main methods for measuring total ice mass changes for Antarctica:

- The mass budget method (Favier et al. 2017) calculates total gain and losses over time as the difference between the estimates of snowfall (input) and glacier outflow across the periphery of the grounded ice sheet (output, from measured velocity and thickness).
- A second method monitors surface elevation changes, primarily using pulsed range-finding radars and lasers from satellites, to determine losses (lowering surfaces) or gains (rising surfaces) and infer mass changes.
- A third method uses gravity satellites to measure deviations in the gravitational pull as they pass over the ice sheet to 'weigh' changes in ice-sheet mass.

Each method has advantages and disadvantages, and relies on different data sources. Consequently, the magnitudes of estimated change vary; however, most studies now broadly agree within their uncertainty estimates.

The Sixth Assessment report by Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC) (IPCC in press-a) synthesised several recent studies and methods to assess the net mass budget. From 1992 to 2017, Antarctica's net mass loss was 2670 ± 530 gigatonnes (Gt) of ice equivalent (Figure 5a). Each 360 Gt of ice mass converts to approximately 1 millimetre (mm) of sea level rise, and the Antarctic ice sheet has contributed an estimated 7.4 ± 1.5 mm to mean sea level rise from 1992 to 2020.

The rate of mass loss from Antarctica has increased over recent decades. The average loss of ice in 1992–2001 was 51 ± 73 Gt per year (Gt/yr). This increased to 82 ± 27 Gt/yr in 2002–11 and again to 199 ± 26 Gt/yr in 2012–17 (Meredith et al. in press). These rates mark an increase on those reported in the 2016 state of the environment report. Much of the difference is due to accelerating mass changes (loss) in both West Antarctica and vulnerable areas in East Antarctica (Table 1).

Mass loss is concentrated around Antarctica's coastal margins, particularly at the ice shelves that fringe the continent. Ice shelves consist of floating ice where the continental ice discharges to the ocean. Importantly, the ice shelves impede the flow of ice discharge from the grounded ice behind. Although removal of floating ice has little direct impact on sea level, the removal of ice shelves allows accelerated discharge from the continent, with a consequent impact on sea level. More than

80% of the continental ice drains through such floating ice shelves (Pritchard et al. 2012).

Assessment of the net mass budget is complex, because of large unknowns associated with the state and rate of change in ocean-driven melting, snowfall and iceberg discharge between regions (Pattyn & Morlighem 2020). Abrupt changes have been observed in some coastal regions, including the rapid disintegration of floating ice shelves (Scambos et al. 2003). This has raised questions about the potential for rapid ice discharge from Antarctica into the sea, particularly from areas that are below sea level. However, because mass loss from floating ice shelves has little effect on sea levels, mass budget calculations focus only on mass gain and loss from the continental ice sheet.

The dominant driver of mass loss from ice shelves in most cases is increased ocean melting (Pritchard et al. 2012, Gudmundsson et al. 2019, Rignot et al. 2019). However, the effects of heat transport by both the atmosphere and the ocean are also important. This is particularly the case on the Antarctic Peninsula (Cook et al. 2005), where atmosphere-driven surface melting and reduced sea ice conditions have caused the rapid disintegration of some ice shelves (Scambos et al. 2003, Massom et al. 2018).

Table 1 Antarctic mass change estimates

Region	2016 SoE report: annual average loss 1992–2011 (20 years) (Gt/yr)	Annual average loss 1992–2017 (25 years) (Gt/yr)	Annual average loss 2012–17 (5 years) (Gt/yr)	Total sea level contribution 1992–2017 (25 years) (mm)
West Antarctica	−65 ± 26	−94 ± 27	−159 ± 26	6.5 ± 1.9
Antarctic Peninsula	−20 ± 14	−20 ± 15	−33 ± 16	1.4 ± 1.0
East Antarctica	14 ± 43	5 ± 46	−28 ± 30	−0.3 ± 3.2
All Antarctica	−71 ± 53	−109 ± 56	−219 ± 43	7.6 ± 3.9

Gt/yr = gigatonnes per year; mm = millimetre; SoE = state of the environment
Note: Estimates of mass loss (negative values) and mass gain (positive values) in billions of tonnes (Gt) of ice differ between regions and time periods.
Sources: 2016 SoE report data from Klekociuk & Wienecke (2016); all other data from IMBIE team (2018), which provides a collation of 24 independently derived estimates of ice-sheet mass balance, derived from the 3 main methods for determining ice loss changes described in the text.

Regional ice-sheet changes

The Antarctic ice sheet consists of 3 geographically different regions:

- the Antarctic Peninsula, which reaches further north than any other area in Antarctica
- the West Antarctic Ice Sheet
- the East Antarctic Ice Sheet, which is by far the largest component, extending from about 30°W to about 165°E.

All recent studies agree that ice losses from the Antarctic Peninsula and the West Antarctic Ice Sheet have increased since the mid-2000s (Bamber et al. 2018, Gardner et al. 2018, IMBIE team 2018, Rignot et al. 2019). These losses represent the main Antarctic contribution to sea level rise.

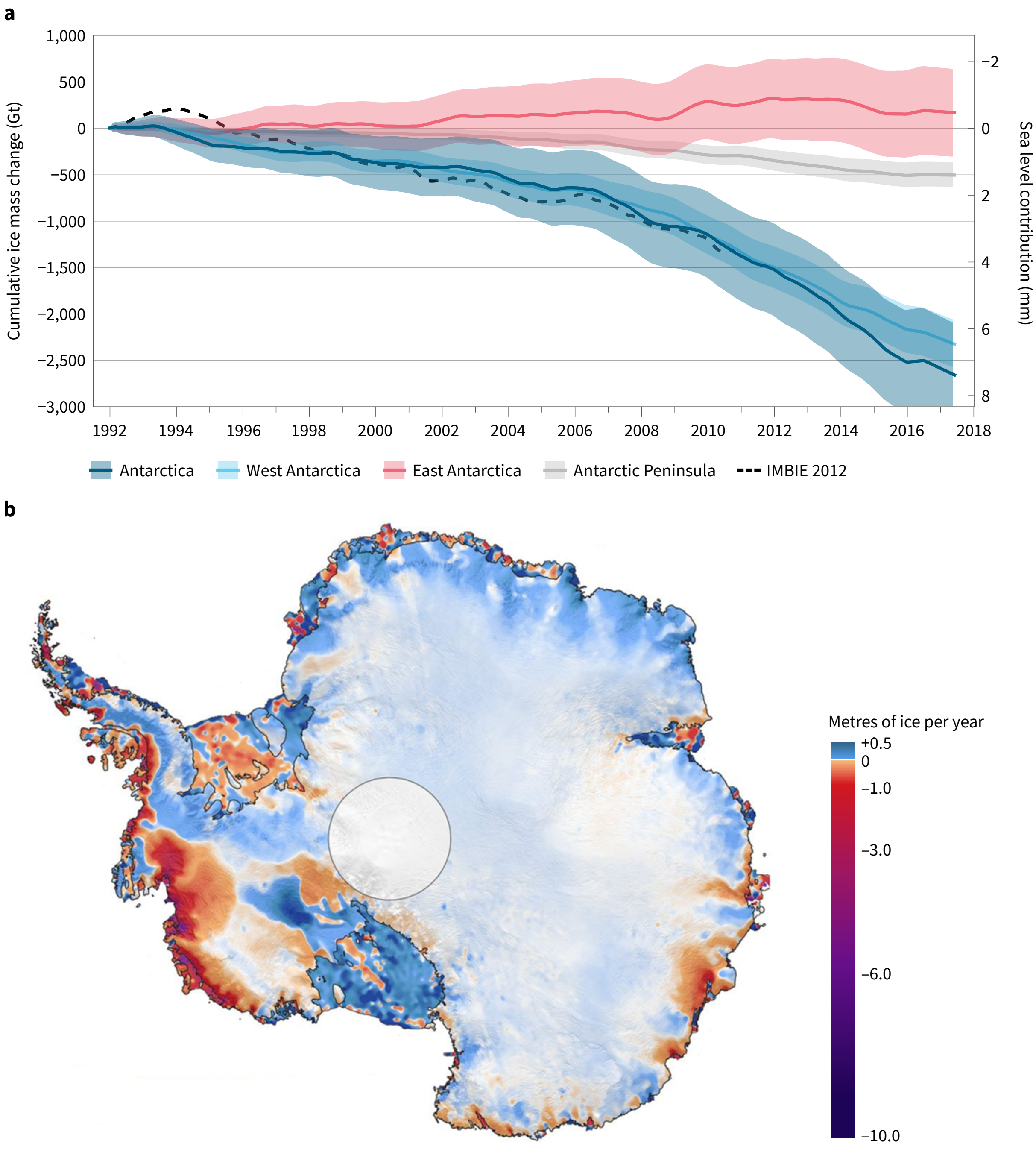
During the latter part of the 20th century, the Antarctic Peninsula experienced one of the highest regional temperature increases on the planet (2.8 °C in 50 years), although this trend has since decreased (Turner et al. 2016). Several floating ice shelves in that region collapsed abruptly – for example, the Larsen B Ice Shelf collapsed in March 2002, and collapse and disintegration of large parts of the Wilkins Ice Shelf occurred in 2008 and 2009 (Steig et al. 2009, Humbert et al. 2010). By 2009, the Antarctic Peninsula had lost about 18% of the area of ice shelves present in the 1950s (Cook & Vaughan 2010), a decline of 28,100 km^2. With the buttressing effect of grounded ice shelves gone, glaciers adjacent to the collapsing ice shelves accelerated to flow approximately 3–4 times faster into the ocean (Scambos et al. 2003, Rintoul 2007). In contrast, other important ice shelves, such as the Amery and Ross ice shelves, have remained comparatively stable (Porter et al. 2019, Zhou et al. 2019).

Changes in West Antarctica have dominated the mass loss from Antarctica to date (Figure 5a). The West Antarctic Ice Sheet has a much larger volume than that of the combined glaciers on the Antarctic Peninsula, and stores enough ice to raise sea levels by 5.3 m (Morlighem et al. 2020). Areas of West Antarctica in contact with warm ocean waters have experienced ice-shelf thinning, and retreat of the grounding line (where the ice shelf starts to float) (Gudmundsson et al. 2019). This change has also spread inland, with grounded ice experiencing thinning and accelerated retreat of the grounding line (Smith et al. 2020).

The grounding line retreat may become irreversible in the near future, as much of West Antarctica sits on a retrograde bed slope (i.e. it slopes downward towards the interior of Antarctica), meaning that grounding line retreats cause a positive feedback (see case study: Vulnerability of the Antarctic ice sheet to future climate change). However, recent evidence suggests that rapid bedrock uplift due to recent ice melt may slow this retreat (Larour et al. 2019).

The situation for the East Antarctic Ice Sheet is more complicated. The East Antarctic Ice Sheet is the largest of the Antarctic ice sheets, and contains enough stored ice to raise sea levels by 52 m. The East Antarctic Ice Sheet appears to be generally close to being in balance or potentially in gain, with mass losses from ocean-driven melt compensated by increased snowfall (Martin-Español et al. 2017, Bamber et al. 2018, Gardner et al. 2018, IMBIE team 2018). The estimates of mass gain are smaller than in the 2016 state of the environment report because several key areas are losing mass at an accelerating rate. Rignot et al. (2019) estimated that the East Antarctic Ice Sheet contributed overall 4.4 ± 0.9 mm to sea level rise over 1979–2017 (approximately 20% of Antarctica's total contribution, or roughly 10% of the global increase over this period).

There are also regional differences in the response of the ice sheet within East Antarctica to climate change (Edwards et al. 2021). Increases in snowfall are concentrated in Queen Maud Land (Velicogna et al. 2014, Smith et al. 2020). Several studies have measured mass loss from Wilkes Land since the mid-2000s (Velicogna et al. 2014, Gardner et al. 2018, Smith et al. 2020). This is of particular concern, as the Aurora and Wilkes subglacial basins are susceptible to irreversible grounding line retreat and rapid destabilisation of the margins of the ice sheet (Mengel & Levermann 2014, Gwyther et al. 2018).



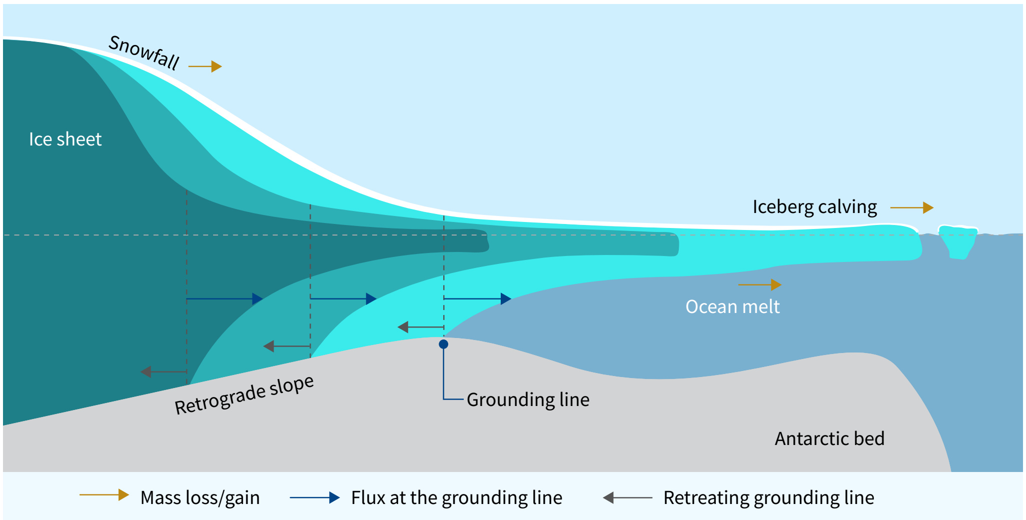
Gt = gigatonne; IMBIE = Ice sheet Mass Balance Inter-comparison Exercise; mm = millimetre
(a) Antarctic mass loss was compiled from 24 separate studies by the IMBIE team (2018). (b) Ice-sheet thinning was measured by Smith et al. (2020) over 2003–19.
Sources: (a) From IMBIE team (2018). Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer, Nature. Mass balance of the Antarctic Ice Sheet from 1992 to 2017, Andrew Shepherd et al., 2018. (b) From Smith et al. (2020). Reprinted with permission from AAAS; permissions conveyed through Copyright Clearance Center, Inc.

Figure 5 Antarctic mass loss

Case study Vulnerability of the Antarctic ice sheet to future climate change

In some regions, ice-shelf thinning and loss carry additional significance for future mass loss because of potential instability of the ice sheet (Figure 6a). In areas where ice is grounded below sea level on a bed that deepens inland, initial ice retreat, once triggered, can lead to accelerated discharge and further retreat, which is irreversible (Schoof 2007). Some studies indicate that this process is already underway in regions of West Antarctica (Rignot et al. 2014).

Regions of East Antarctica known to be changing are associated with regions thought to be vulnerable to this type of retreat process. Recent work mapping the bed beneath the East Antarctic Ice Sheet reveals extensive areas grounded below sea level that may be similarly vulnerable to loss (Roberts et al. 2011, Young et al. 2011, Fretwell et al. 2013). In East Antarctica, there are 2 regions where future large-scale retreat could occur (Figure 6b). The Wilkes and Aurora subglacial basins each cover extensive areas of ice grounded more than 1 km below sea level. Ice thinning and loss in the margins of these regions may lead to large-scale retreat on centennial timescales (Golledge et al. 2015, Pollard et al. 2015).



Notes:
1. Marine ice-sheet instability (MISI) causes regions of the ice sheet on retrograde slopes to be vulnerable to irreversible retreat, as any retreat of the grounding line increases flux and thinning.
2. Regions of East Antarctica vulnerable to MISI include the Wilkes and Aurora subglacial basins.

Source: Produced using the Norwegian Polar Institute's Quantarctica package.

Figure 6 East Antarctic vulnerability to ice retreat

Heard Island glaciers

On Heard Island, the glaciers have retreated since the first measurements in the 1940s, and have continued to retreat over the past decade. The first aerial survey of the glaciers on Heard Island was in the 1940s, and the glaciated area of the island was 288 km^2. The glaciated area had decreased to 256 km^2 by the 1980s (Ruddell 2006), to 236 km^2 in 2012 and to 235 km^2 in 2014. The most recent survey from 2016 of the larger Big Ben glaciers (Baudissin, Challenger, Downes, Ealey, Compton, Brown, Fifty-One, Gotley and Lied glaciers) indicated that there has been a further decrease in the area of these larger glaciers since the 1940s (Donoghue 2021).

Examination of more recent satellite images of the eastern glaciers indicates that these leeward glaciers continue to retreat at greater rates than those on the windward side of the island. For example, the 2011 and 2016 state of the environment reports stated that Brown Glacier had retreated from an area of 6.2 km^2 in 1947 to 4.4 km^2 in 2004, 3.6 km^2 in 2008 (Lucieer et al. 2009, Harris 2018), 3.5 km^2 in 2014 (Donoghue & Harris 2017) and 3.4 km^2 in 2016. This represents a total loss of 45% since 1947 (Donoghue 2021). As of January 2019, Brown Glacier had continued to retreat. The overall retreat of glaciers over 2000–19 was reported by Hugonnet et al. (2021) for Heard Island, as well as in other subantarctic regions, including the Kerguelen Islands, South Georgia and nearby islands.

Big Ben, a stratovolcano that rises to 2,745 m above sea level, has been frequently active since the 1910s. Because of the remoteness of the island and infrequent visits, most of the recent reports of volcanic activity have been from Middle InfraRed Observation of Volcanic Activity (MIROVA) analysis of satellite imagery. The most recent eruptive activity, reported by the Global Volcanism Program et al. (2020), occurred from October 2019 to March 2020. As is typical of Heard Island, cloud cover persisted over this period, but a possible lava flow – apparent as a hotspot – appeared to have extended south-west from the summit.

Sea ice

Antarctic sea ice plays a crucial role in the climate system, as well as the structure and function of high-latitude Southern Ocean ecosystems. Sea ice around Antarctica has 2 main components. The most extensive is ‘pack ice’, which is made up of individual pieces called ‘floes’ that are in constant motion in response to winds and ocean currents. The other main component is stationary (nondrifting) ‘fast ice’, which forms as a narrow band of compact sea ice generally tens of kilometres, but up to 250 km, wide. Fast ice is confined to Antarctica’s coastal margins, where it is held in place by icebergs grounded in waters shallower than about 450 m, coastal promontories, islands and sheltered embayments (Fraser et al. 2020). This form of floating ice is of key significance in coastal and ice-sheet processes and ecosystems (Massom et al. 2010, Massom & Stammerjohn 2010). It is also of importance to human operations where, for example, it can aid or hinder the discharge of heavy cargo and personnel from ships to Antarctic stations.

Sea ice changes

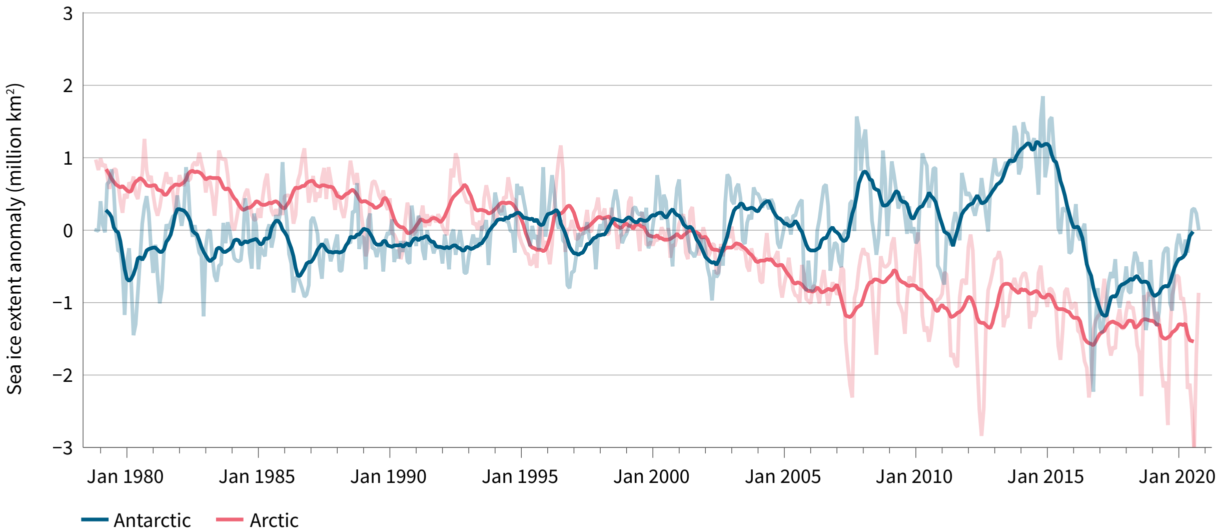
Sea ice in the Arctic and Southern oceans has different characteristics and patterns of large-scale change because of differences in geographical settings and the processes affecting them. Whereas landmasses largely enclose the sea ice in the Arctic Ocean, Antarctic sea ice surrounds the continent and is constantly exposed to Southern Ocean storms and waves.

Based on a consistent satellite record since 1979, overall Antarctic sea ice extent increased by 1.0 ± 0.5% per decade (about 11,300 km^2

per year) over 1979–2018 (Parkinson 2019), although the trend in sea ice area over 1979–2020 is not considered significant (IPCC in press-b). The past few years of the record have shown considerable interannual fluctuations (Figure 7; see case study: An extreme decline in Antarctic sea ice in 2016, for a discussion of recent annual records). Much of this increase occurred from 1979 to 2014. The years 2012, 2013 and 2014 set successive records for high sea ice extent (Reid & Massom 2015); this was followed by a sharp switch to record low extents for particular months during 2017–19. In contrast, Arctic sea ice over 1979–2020 decreased by 13.1% per decade (82,700 km^2 per year) relative to the 1981–2010 average (Perovich et al. 2020).

The overall trend in Antarctic sea ice extent masks strong regional (Parkinson 2019) and seasonal (Holland 2014) trends that are influenced by large-scale modes of climate variability (Yang et al. in press). Whereas sea ice extent decreased by 2.5 ± 1.2% per decade in the Amundsen and Bellingshausen seas sector for 1979–2018, other sectors displayed increases, ranging from +1.0 ± 0.8% per decade in the Weddell Sea to +2.3 ± 1.2% per decade in the south-west Pacific Ocean (Parkinson 2019).

Contrasting regional patterns of change are also apparent in the annual seasonality of sea ice coverage around Antarctica, compared with more uniform change around the Arctic (Stammerjohn et al. 2012). In the Amundsen, Bellingshausen and north-western Weddell seas, annual sea ice duration lengthened by about 2–3 months from 1979 to 2016 (Stammerjohn & Maksym 2017), due to a 1–2-month later ice advance in autumn and a 1-month earlier spring–summer retreat. In the western Ross Sea, the annual ice season lengthened by about 2–3 months due to earlier advance and later retreat. Across East Antarctica and within the AAT, the changes in the annual duration of sea ice are generally smaller and vary across zones (Hobbs et al. 2016a), with localised positive and negative trends (Massom et al. 2013).



km^2 = square kilometre
Note: Figure shows anomaly (difference from climatological average) of monthly mean (lighter lines) and 11-month running mean (darker lines) sea ice extent in the Arctic and Antarctic since 1979.
Source: Adapted from Turner & Comiso (2017) and extended using data from the National Snow and Ice Data Center.
Credit: Phillip Reid, BOM

Figure 7 Sea ice extent anomaly

Unexpected high variability has occurred in the overall Antarctic sea ice extent since 2012. Persistent daily positive anomalies and record highs of total sea ice extent in 2012 to mid-2015 (Reid & Massom 2015) were followed by an abrupt change to daily negatives and record lows from 2016 to early 2020 (Meehl et al. 2019, Parkinson 2019). The Weddell Sea made the largest contribution to the post-2016 decrease (Turner et al. 2020b).

In addition to sea ice extent, sea ice thickness and volume are important variables to monitor. However, available information is inadequate to determine whether large-scale sea ice thickness and therefore volume are changing around Antarctica (IPCC in press-a). Surface, air and under-ice observations of Antarctic sea ice thickness are sparse (Worby et al. 2008), as are measurements of snow cover depth (Webster et al. 2018). Estimates of Antarctic sea ice thickness and associated snow depth are emerging from analysis of satellite altimeter datasets (Paul et al. 2018, Kacimi & Kwok 2020), but definite trends are yet to emerge. Validation of the satellite-derived thickness estimates is a challenge (Newman et al. 2019). This is a critical knowledge gap because the global climatic importance of Antarctic sea ice stems in large part from the volume of ice that freezes and melts each year, rather than from the coverage alone.

In the 2016 state of the environment report, trends in fast ice extent in East Antarctica could not be identified with confidence because of the short (8.8-year) satellite timeseries of fast ice available (Fraser et al. 2012). Recent work on mapping the distribution and extent of fast ice around Antarctica has shown evidence of a small decline in the total coverage from 2000 to 2018 (Fraser et al. 2020).

Causes of sea ice changes

Several factors may contribute to the observed increase in overall Antarctic sea ice coverage during 1979–2014, and its pronounced regional and seasonal variability (Matear et al. 2015, Hobbs et al. 2016b). These include:

- strengthening of the Southern Ocean westerly winds encircling the Antarctic continent and associated cooling of surface waters (Armour & Bitz 2015)
- changes in atmospheric pressure patterns around Antarctica, and associated meridional winds and temperature, as they drive sea ice drift, formation and melt (Holland & Kwok 2012, Haumann et al. 2014).

Uncertainty remains as to causes of the dramatic, unanticipated decrease in overall Antarctic sea ice extent after 2016, which has been attributed to a complex combination of atmospheric and oceanic forcing (Kusahara et al. 2019, Meehl et al. 2019, Turner et al. 2020b), with differing regional contributions (Reid et al. 2020).

Because of large interannual variability and the relatively short duration of observations, changes in sea ice cover are too small to be separated from natural variability in the climate system (Hobbs et al. 2016a). Current climate models do not adequately simulate the observed patterns of change and variability in sea ice extent and seasonality since 1979 (Hobbs et al. 2016b, National Academies of Sciences 2017). This also confounds our ability to detect and attribute changes in sea ice cover. The model deficiencies relate to inaccurate understanding and parameterisation of the complex interactive processes and feedbacks within the southern sea ice–atmosphere–ocean–ice-sheet system and the various anthropogenic (human) forcings involved (i.e. greenhouse gases and ozone), together with decadal-scale natural variability (Notz & Bitz 2017).

Impact of sea ice changes

Given the pivotal role of sea ice in driving water mass transformations in the Southern Ocean (Abernathey et al. 2016, Pellichero et al. 2018), changes in sea ice distribution, properties and processes have strong potential to affect overturning ocean circulation and climate on decadal and longer timescales (Bindoff & Hobbs 2016, IPCC in press-a). Sea ice changes are also influencing the physical state of the Southern Ocean. An increase in wind-driven sea ice export of 20 ± 10% from 1982 to 2008 has produced ocean freshening (reduction in salt content per mass of seawater) of 0.002 ± 0.001 grams per kilogram per year in intermediate and surface waters (Haumann et al. 2016).

Regional sea ice changes also have indirect consequences for sea level rise. Sea ice loss to the west and north-west of the Antarctic Peninsula has been implicated as a trigger mechanism for the catastrophic rapid disintegration of 3 major ice shelves (Larsen A, Larsen B and Wilkins) since 1995, by increasing the exposure of damaged (highly crevassed) ice-shelf margins to destructive ocean swells (Massom et al. 2018).

There is growing evidence from the Arctic that sea ice loss has influenced mid-latitude seasonal climate in the Northern Hemisphere (IPCC in press-a). For the Southern Hemisphere, modelling suggests that changes in Antarctic sea ice appear to have had a comparatively smaller effect on climate (England et al. 2018). Projected future Antarctic sea ice loss will potentially increase warming and precipitation changes in the tropics (England et al. 2020).

Although relatively little is known about the overall environmental, ecological and climatic impacts of observed Antarctic sea ice change and variability compared with the Arctic (Meredith et al. in press), evidence is emerging that these impacts can be significant on both local and global scales. As detected by the Palmer Long-Term Ecological Research program, declining sea ice extent and annual duration west of the Antarctic Peninsula have had substantial and cascading impacts on ecosystem food-web structure and function, and biodiversity (Ducklow et al. 2013). Sea ice changes have been linked to:

- changes in primary production (phytoplankton species)
- a poleward migration of ice-dependent penguin and seal species due to habitat contraction and impacts on foraging success (prey distributions)
- the incursion (poleward migration) of subantarctic and warmer-water species.

Less clear are potential influences of sea ice change on the distribution of Antarctic krill (*Euphausia superba*), which is a major fishery, and a keystone prey species for fish, penguins, seals and whales (Atkinson et al. 2019).

These changes and their impacts are projected to continue and increase. Net marine primary production around Antarctica is predicted to increase in response to sea ice loss, warming and changing nutrient supply, due to shifts in ocean stratification and upwelling (IPCC in press-a). The habitat of krill in the Southern Ocean is projected to contract southward (IPCC in press-a). Current large uncertainty in future Antarctic sea ice conditions, however, poses challenges to the accurate assessment of potential impacts on logistical operations in support of Antarctic stations (involving both ships and aircraft), fishing, marine research vessels and tourism activities (Chown 2017).

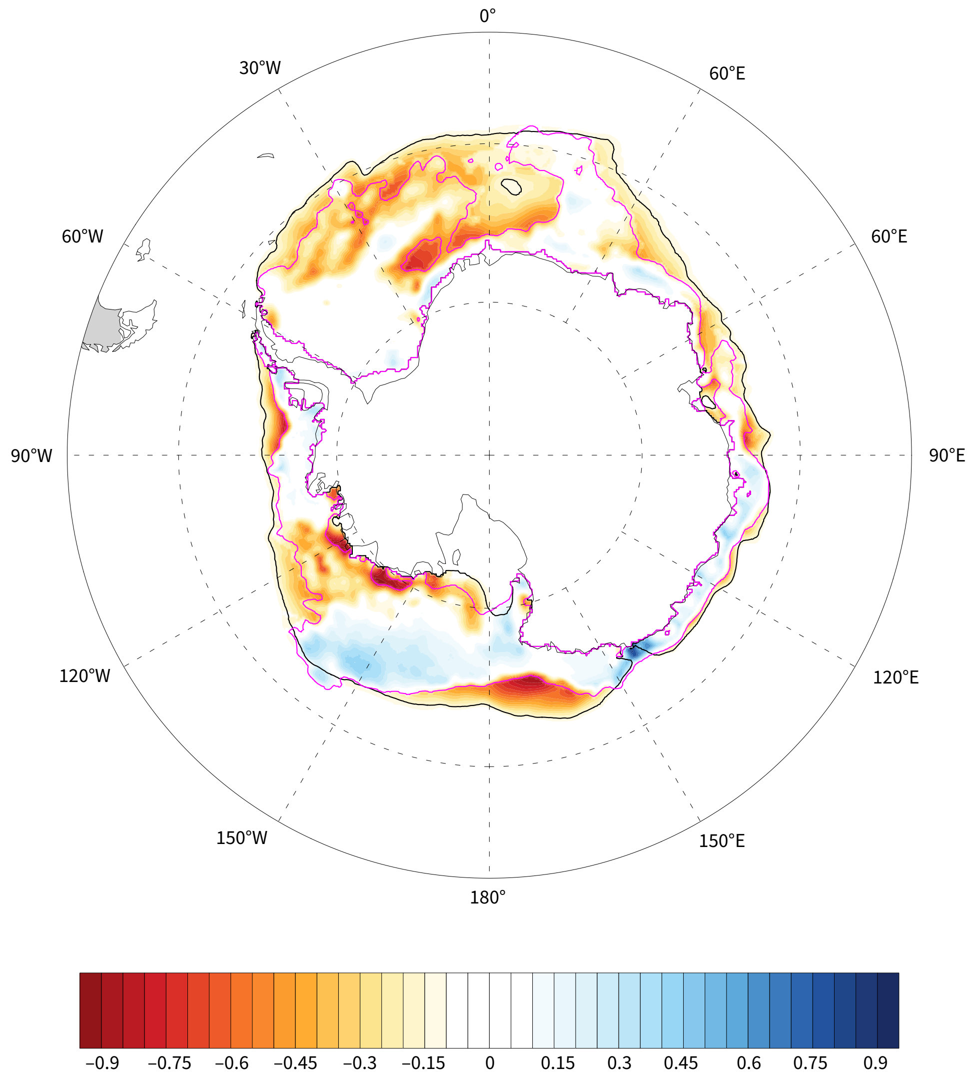
Case study An extreme decline in Antarctic sea ice in 2016

In mid-2016, the overall Antarctic sea ice extent declined suddenly and rapidly (Parkinson 2019). This followed decades of a gradual increasing trend and occurred immediately after a persistent period of well-above-average coverage in 2012–15 (Reid & Massom 2015). By the 2016–17 summer, the sea ice area had reached its lowest recorded anomaly (since 1979) by some margin. This event was remarkable not just for its magnitude but also for its timing, starting a month or so before the usual start of the spring melt and ice-edge retreat (Reid et al. 2017). The sea ice loss was widely distributed; the Australian Antarctic Territory sector was the only region without a significantly reduced sea ice cover (Figure 8) during this event.

This unprecedented and unanticipated event has challenged our understanding of Antarctic sea ice and the processes driving change and variability.

Most of the research to date on this event has focused on the role of the atmosphere. The event followed a significant El Niño in 2015–16, which may have preconditioned the ocean–sea ice system for a sudden sea ice loss (Nicolas et al. 2017, Stuecker et al. 2017, Schlosser et al. 2018). However, previous stronger El Niño events have not resulted in such losses. Several studies have focused on the impact of a very unusual atmospheric circulation in late 2016, with weak westerly winds but anomalously strong alternating meridional (i.e. northerly and southerly) winds (Stuecker et al. 2017, Turner et al. 2017, Wang et al. 2019). This atmospheric anomaly certainly contributed to the spring decline, but only really developed in October, after the retreat had begun in August (Reid et al. 2017). There is evidence that the ocean played a significant role (Meehl et al. 2019), and this is a subject of ongoing research.

Overall sea ice coverage partially recovered in the 2017 winter (Reid et al. 2018), although summer sea ice extent remained below average until 2020–21, suggesting that this was a relatively short-lived event, rather than a dramatic start of the projected decline in Antarctic sea ice. However, it is unknown at this stage whether there was an anthropogenic influence on this abrupt and dramatic event, or whether the likelihood of such events will increase in future.



Note: The anomaly is shown with respect to the 1979–2008 December mean. The black line shows climatological ice edge; the magenta line shows December 2016 ice edge.
Source: Goddard merged sea ice concentration (Peng et al. 2013)
Credit: Dr Will Hobbs, Australian Antarctic Program Partnership

Figure 8 December 2016 sea ice concentration anomaly

Assessment State and trends of Antarctic sea ice, the ice sheet and Heard Island glaciers

2021

Very poor | Poor | Good | Very good

Adequate confidence

The state of Antarctic ice is generally good, but the trend is unclear, with high variability between seasons and years. Subantarctic glaciers are retreating.

Assessment Sea ice extent

2021

Very poor | Poor | Good | Very good

2016

Good

2011

Good

Adequate confidence

A slight increase in overall areal coverage since 1979, but made up of contrasting regional and seasonal contributions. A sudden shift to high variability in 2012–20, with record highs followed by record lows (after 2016). Attribution remains uncertain.

Assessment Sea ice seasonality

2021

Very poor | Poor | Good | Very good

2016

Poor

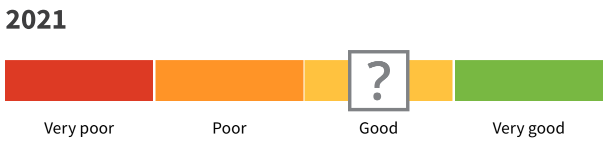
2011

Poor

Adequate confidence

Decreased duration of annual sea ice coverage in the Amundsen, Bellingshausen and north-west Weddell seas since 1979; increased duration in the Ross Sea; and mixed signals across East Antarctica.

Assessment Fast ice extent



Adequate confidence

A small, marginally significant decrease in circumantarctic fast ice extent for 2000–18.

Assessment Sea ice (and snow cover) thickness

Low confidence

Insufficient information to date to determine whether large-scale sea ice and snow cover thickness is changing around Antarctica.

Assessment East Antarctic Ice Sheet mass balance

Adequate confidence

Indications of a net mass loss over 2012–17, although this is not statistically significant.

Assessment Heard Island and McDonald Islands, and other subantarctic glaciers

Adequate confidence

Glaciers are generally retreating.

Southern Ocean

The Southern Ocean surrounds Antarctica and covers 14% of the planet's surface; it plays a key role in global climate and the global carbon cycle (Fogwill et al. 2020). It connects the 3 main ocean basins (Atlantic, Pacific and Indian) and strongly influences the global oceanic circulation system through the Antarctic Circumpolar Current (ACC), the world's largest oceanic current (Rintoul 2018). The ACC flows from west to east around Antarctica and generates an overturning circulation that transports vast amounts of heat. The ACC also takes up a significant amount of carbon dioxide (CO_2) from the atmosphere (Rintoul et al. 2001, Rintoul 2018). The formation and circulation of Southern Ocean water masses provide a key link in the global 'conveyor belt' of ocean currents that controls climate by transporting heat and other properties (see Sea ice). The Southern Ocean influences the mass balance of Antarctica by influencing air temperatures, winds and precipitation, particularly near the coast, and the melting of ice sheets and coastal ice (Holland et al. 2020).

The Southern Ocean is changing in ways that are likely to affect regional and global climate (Rintoul et al. 2018, Meredith et al. in press), and marine productivity (Rhein et al. 2013, Deppeler & Davidson 2017, Boyd 2019). The changes include warming and acidification (see Pressures), as well as changes to ocean properties, circulation and sea level.

Ocean properties

At Southern Hemisphere latitudes north of about 50°S, the surface temperature of the Southern Ocean has shown a warming trend in recent decades (Sallée 2018). However, south of about 50°S towards the Antarctic coast, the surface waters have, on average, cooled and freshened (Durack et al. 2012, Swart et al. 2018, Bronselaer et al. 2020). These high-latitude changes are likely to reflect mainly increases in precipitation and Antarctic ice melt (Böning et al. 2008, Helm et al. 2010), and ocean upwelling (Armour et al. 2016, Hogg et al. 2017, Tamsitt et al. 2017). Antarctic bottom water in some locations has warmed, freshened and decreased in volume (van Wijk & Rintoul 2014, Sallée 2018); however, there has been a reversal of the freshening trend in recent years in the Australian–Antarctic basin, with near-bottom salinities in 2018–19 higher than during 2011–15 (Aoki et al. 2020).

Ozone depletion and increases in atmospheric greenhouse gases caused by human activities have resulted in changes in wind patterns in southern subpolar latitudes, which have influenced the heat content, salinity and dissolved oxygen content of the Southern Ocean (Turner et al. 2014, Rintoul et al. 2018, Swart et al. 2018).

Sea level rise

Over much of the global ocean, sea level is rising, and the rise is accelerating. The global mean sea level change obtained from tide gauges and altimetry observations increased from 3.2 mm/yr over 1993–2015 to 3.7 ± 0.5 mm/yr over 2006–18 (IMBIE team 2018). Glacier and ice-sheet contributions are now the main source of the rise, and these are associated with anthropogenic (human) forcing (Meredith et al. in press).

The rate of change of sea level has been regionally and globally variable in recent decades because of influences from natural climate variability and volcanic events. The influence of natural variability is noticeable particularly where the ocean is cooling, and hence, contracting; this can be caused by the ENSO mode of large-scale climate variability.

The rate of sea level rise is expected to increase because of continuing global warming

(Fasullo et al. 2016). The fate and response of the ice sheets to global warming are the greatest source of uncertainty impeding constrained projections of future sea level estimates; the likely upper bound is 25 m of sea level for a climate that is 2–4 °C warmer than pre-industrial temperatures (Carson et al. 2019, Meredith et al. in press).

In the Southern Ocean, sea level is difficult to measure because of the presence of sea ice around the continent, which impedes altimetry observations of the surface, and influences from the ongoing unloading of forces on bedrock after the last ice age. From 1970 to 2018, most of the Southern Ocean increased in height; the region between 30°S and 60°S showed accelerating trends that were among the largest anywhere on the globe (Church et al. 2013, Wang et al. 2021). Over this period, parts of the Pacific sector fell modestly, which is ascribed to upwelling of cold waters near the Antarctic coast (Armour et al. 2016).

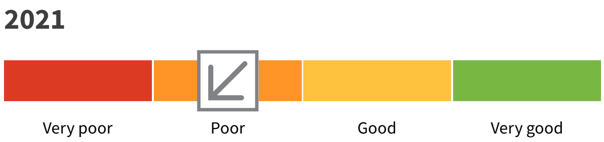
Marine heatwaves

Marine heatwaves (MHWs) are events occurring in the global oceans during which water temperatures are anomalously warm (up to several degrees Celsius above average) for extended periods (typically days to a few weeks). These events can have disruptive influences on marine ecosystems and their biodiversity, and regional fisheries (Holbrook et al. 2020, Samuels et al. 2021, Su et al. 2021). Several physical processes can produce MHWs. These can be broadly categorised as alteration of the oceanic heat transport, influences from slowly changing atmospheric patterns, and effects from large-scale modes of climate variability associated with ocean–atmosphere coupling (Holbrook et al. 2019, Sen Gupta et al. 2020).

Oliver et al. (2018) provided a global assessment of MHWs using a range of ocean temperature data. Over 1982–2016, MHWs have increased in frequency in northern parts of the Southern Ocean, particularly in the central Pacific sector, where the trends have been consistent with ocean warming. However, at latitudes poleward of 50°S, MHWs have decreased in frequency in recent decades (Oliver et al. 2018), particularly in the central Pacific sector, where ocean cooling has been observed (Haumann et al. 2020). Although none of the major climate modes dominantly result in MWHs in the Southern Ocean, some regions are preferentially affected by the SAM, ENSO and the Interdecadal Pacific Oscillation (Holbrook et al. 2019).

The impact of potential changes in the characteristics of MHWs in the Southern Ocean and coastal Antarctica is of concern, because food webs are adapted to a specific range of conditions. Recent model assessments suggest that MHWs will generally increase in frequency and duration over coming decades across all oceans, and lead to greater environmental effects. However, an exception is the coastal region of East Antarctica, where changes in the intensity of heatwaves are not projected to be significant (Oliver et al. 2019, Hayashida et al. 2020) because ocean warming in this region is relatively slow.

Assessment State and trends of the Southern Ocean



Adequate confidence

Climate change is having a significant impact on the Southern Ocean. Changes in temperature, acidity, salinity and sea level are generally assessed as poor and deteriorating, although ocean temperature varies across the region.

Assessment Ocean temperature

Adequate confidence

Temperature changes have been mixed in magnitude, and depend on depth and geographic region.

Assessment Ocean acidity

Adequate confidence

Polar pH levels are changing twice as fast as in the tropical ocean. Pre-industrial acidity has increased; pH has changed from 8.2 to 8.1.

Assessment Ocean salinity

Adequate confidence

The surface waters have freshened in recent decades.

Assessment Sea level

Adequate confidence

Global sea levels are rising because of uptake of heat, and run-off from ice caps and glaciers. The rate of change shows regional and global variation with time because of certain aspects of climate variability.

Living environment

Antarctic species occupy diverse habitats and ecosystems that include ice-covered areas, ice-free vegetated areas, ice-free rocks, salt and freshwater lakes and streams, intertidal areas, sea ice, middle and deep water, and benthic regions of the Southern Ocean (the benthic zone is the ecological region at the bottom of the ocean, including the sediment surface and some subsurface layers). Permanent ice and snow cover almost the entire Antarctic continent, and permanent or seasonal ice-free areas of exposed rock are rare (Bockheim 2015, Burton-Johnson et al. 2016).

Species that have made Antarctica their home have evolved over many millions of years. The Drake Passage opened about 30 million years ago, isolating Antarctica from other continents. Antarctic terrestrial species have adapted physiologically to cope with the significant environmental challenges they encounter: freezing temperatures, extensive ice cover, extended periods of reduced sunlight and poor soil quality. In addition, despite its vast ice cover, Antarctica lacks persistent free-flowing water, so that most, if not all, terrestrial vegetation freeze-dries to survive winter when liquid water is not available for life (Kawarasaki et al. 2019).

Antarctic plants (mosses, lichens and algae), microorganisms and invertebrates comprise a generally highly specialised flora and fauna that are less diverse than in temperate regions but often locally abundant. In Antarctica, the most diverse and abundant terrestrial biodiversity is invisible to the human eye and contained in the soils and water bodies. Because of their high specialisation, many species are endemic (found nowhere else) (Velasco-Castrillón & Stevens 2014, Biersma et al. 2018, Biersma et al. 2020). Metagenomics or environmental genomics – the study of genetic material obtained from a mixture of microorganisms collected from the environment – is rapidly improving our understanding of microbial community structure and composition, and the extent of biodiversity of the microcosm. Genetic analyses using mitochondrial or genomic DNA are used in studies of higher organisms such as seabirds, and are detecting more differentiation or population structure among species than previously assumed (e.g. Frugone et al. 2018, Rexer-Huber et al. 2019).

Terrestrial species

In the Antarctic terrestrial environment, environmental gradients, such as salinity and ice cover, are more pronounced than anywhere else on Earth. Ecosystems are also often highly isolated, especially in the terrestrial environment where areas are snow- and ice-free (Convey et al. 2014). In 2012, Antarctica's ice-free areas were classified into 15 Antarctic Conservation Biogeographic Regions (ACBRs) based on differences in biodiversity and landscape features (Terauds et al. 2012); in 2016, a 16th ACBR was added (Terauds & Lee 2016). Biogeographic regions have become an important management tool for the conservation of biologically distinct areas.

Many Antarctic terrestrial species depend on the ice-free areas of the continent and its offshore islands, but only approximately 54,200 km^2, or 0.44%, of the total Antarctic land mass is ice-free (Brooks et al. 2019). Ice-free areas are either isolated mountain peaks, mountain ranges, dry valleys, exposed coastal fringes or offshore subantarctic islands. Most ice-free areas occur in the Transantarctic Mountains, which extend over 3,500 km and separate East from West Antarctica, and the Antarctic Peninsula.

In some ice-free areas, freshwater and saline lakes exist that range in size from small tarns, which freeze solid in winter, to large and deep lakes in which water remains liquid throughout the year. The species composition varies in freshwater, brackish and saline water bodies. The organisms inhabiting saline lakes originated mainly from marine species. The surface of lakes is typically frozen; in coastal areas, this layer of ice can melt in summer.

One of East Antarctica's few oases (coastal ice-free areas) is the Vestfold Hills area. Here occurs the greatest concentration of permanently stratified (meromictic) water bodies in Antarctica, and possibly the world (Gibson 1999). Meromictic lakes are usually deep, with steep sides. Since the water layers do not intermix, different light, oxygen and salinity levels occur in different zones. Biodiversity can be high among the different, specialised communities in the aerobic and anaerobic zones (Gibson 1999, Lauro et al. 2011). The 2 main habitats in Antarctic lakes are the water column and the benthic mat. The latter is a mixture of algae, bacteria and mosses that covers the bottom of lakes and supports a community of grazing microinvertebrates.

Human activities mostly affect ice-free areas, as these are often in areas where people build Antarctic stations and other infrastructure. Some 81% of all Antarctic buildings are currently located in coastal, ice-free areas (Brooks et al. 2019). Human presence has led to physical disturbance and permanent modification of habitats (Brooks et al. 2019), reduction of aesthetic values (Summerson & Bishop 2012) and changes in geomorphology (Campbell et al. 1994). Even in areas where human activities have ceased, tracks of vehicles were still discernible 60 years later (O'Neill et al. 2013).

Climate change is likely to enlarge the ice-free areas in Antarctica – possibly by as much as 25% – by the end of the century. Most of this gain will occur in the Antarctic Peninsula region, currently one of the fastest-warming areas. As the physical constraints imposed on terrestrial life by the vast areas of ice are diminishing, the range of certain species will possibly expand. However, other factors potentially limiting distributions, such as water, will also play a role (Lee et al. 2017).

Whereas some native organisms may expand their distributions, others may not survive in the long term as temperatures rise. Changes in the species composition of soil organisms have occurred in the McMurdo Dry Valleys, Ross Sea. The dominant species, a nematode, has decreased, while other less dominant taxa have increased. However, the overall trend indicates a general decrease in the abundance of soil biota (Andriuzzi et al. 2018). Environmental changes may also enable non-native, invasive species to establish (see Non-native species) (Duffy & Lee 2019).

Invertebrates

Multicellular terrestrial animals that live in Antarctica throughout the year are limited to a few types of invertebrates able to withstand the environmental conditions. Many microinvertebrate species live in the benthic mats associated with lakes; some inhabit only the water column; others survive in the adjacent soils. There is some overlap in species that occur in aquatic and soil habitats. The most abundant phyla are rotifers, nematodes and tardigrades, but crustaceans, mites and springtails (microarthropods) occur as well (Gibson et al. 1998, Convey et al. 2008, Nielsen et al. 2011).

Compared with temperate regions, the terrestrial invertebrate species diversity of the region is low. Since Antarctica is an isolated continent, many of the species here are endemic, and most communities have persisted throughout several glacial cycles over millions of years (Iakovenko et al. 2015). More than 520 species of invertebrates occur, belonging to 140 genera in 70 families.

Of these, 16 genera and 1 family are endemic (Pugh & Convey 2008). There is only 1 endemic insect, the Antarctic midge (*Belgica antarctica*) (Potts et al. 2020).

Climatic and hydrological conditions, including snow accumulation, can influence habitats available for soil communities, especially in arid ecosystems. The abundance of soil microinvertebrates varies regionally and depends on the conditions of the local microhabitats, particularly topography, salinity, moisture and vegetation (Kennedy 1993, Nielsen et al. 2011, Velasco-Castrillón et al. 2014).

Invertebrates experience highly variable environmental conditions related to water and temperature on various timescales (daily to annual) and are well adapted to cope with these variations. For example, some invertebrates, such as certain nematodes, rotifers and tardigrades, can dry out (desiccate) when water is extremely limited at low temperatures (Nielsen et al. 2011). Long-term records and experimental data show that the various groups of invertebrates respond differently to a warming environment. For example, nematode densities appear to increase when temperatures rise, whereas collembolans respond negatively, particularly when soil moisture is low. Among mites, responses are more complex and appear to be species-specific (Nielsen & Wall 2013).

Antarctic fungi

More than 1,000 species of fungi have been identified in Antarctica, but the true number is likely to be much greater (Bridge & Spooner 2012). Fungi exist as lichen symbionts but also occur as free-living soil fungi, which play an important role in the decomposition of organic matter and soil formation. Free-living fungi are either filamentous or yeasts. There may be well over 1,000 species of free-living fungi, but the taxonomic composition of soil fungi has not yet been studied in a wide range of Antarctic soils (Newsham et al. 2021). Fungal assemblages comprise both worldwide and endemic species. The latter are recognised as true psychrophilic (cold-adapted) species, in contrast to psychrotolerant (cold-tolerant) species that have adapted to life in polar regions (Rosa et al. 2019). Fungal spores can be trapped in glacial and subglacial ice, where some survive for 10,000–140,000 years (de Menezes et al. (2020); and references therein).

During the summer, temperatures of soil surfaces can exceed 19 °C (Perera-Castro et al. 2020, Robinson et al. 2020). At very high temperatures for Antarctica, the growth of soil fungi may be impaired when water availability, and organic nitrogen and carbon levels increase. For example, under such conditions in the maritime Antarctic, metabolic processes were impaired in the most common soil fungus, *Pseudogymnoascus roseus*; the fungus's capacity to extend its hyphae was reduced, and hence its ability to find nutrients. At the same time, organic soil compounds experience reduced decomposition. Ultimately, a reduction or loss of these processes affects the soil ecology and may limit soil development in the Antarctic region (Misiak et al. 2021).

Since Antarctic free-living fungi tend to be cold-tolerant rather than cold-adapted, warming temperatures may not immediately affect their survival. Fifty species of fungi isolated from ornithogenic (formed from bird faeces and debris) soils grew at 37 °C under laboratory conditions (de Sousa et al. 2017). Various Antarctic fungal species are closely related to species that are known pathogens to animals and plants in more temperate regions. There is some concern that Antarctic fungi may have inherent potential to be pathogenic and that they could inadvertently be transported by animals and/or people to other continents (Bridge & Spooner 2012, Rosa et al. 2019).

However, fungi may offer opportunities for bioprospecting (the exploration of natural sources for molecules, and development of genetic and biochemical information into commercially valuable products) – for example, for the development of new drugs. Bioactive compounds with antiviral properties – for example, against dengue and Zika viruses – have been discovered in fungal extracts (Gomes et al. 2018).

In areas where fuel spills and spillage may occur, aromatic and aliphatic hydrocarbons enter the local environment, and can persist in soils and sediments at high concentrations for decades (Gore et al. 1999, Revill et al. 2007, Powell et al. 2010). Whereas some Antarctic mosses and algae are relatively tolerant to diesel contamination (Nydahl et al. 2015), terrestrial invertebrates are expected to be more sensitive (Mooney et al. 2019). Hydrocarbon contamination in soil results in a significant shift in the soil microbial community, favouring copiotrophic species (organisms found in nutrient-rich environments, especially carbon) and known hydrocarbon degraders at the expense of oligotrophic species (organisms living in nutrient-poor conditions) (van Dorst et al. 2021).

Bioremediation of diesel-contaminated soil through biopiling has been successfully demonstrated at Australian Antarctic stations (McWatters et al. 2016a).

Other yeasts have a considerable tolerance for heavy metals and may become useful as an inoculant in wastewater treatments in cold environments (Fernández et al. 2017b).

As air and soil temperatures increase due to climate change, the composition of fungal communities and assemblages is likely to change. The species richness of fungal symbionts of lichens is likely to increase, because they may be able to switch from a state of survival to a state of growth as the availability of free water also increases (Green et al. 2011).

Soil microorganisms

In Antarctica, soils occur only in the small areas that are ice-free. Antarctic soils form very slowly (Mergelov et al. 2020) because the absence of vascular plants and low temperatures limit soil formation. The major soil-forming process is cryoturbation, the constant freeze–thaw cycle that mixes the soil layers (Fisher 2014). Antarctic soils generally form under lichen and moss beds (mineral soils) (Mergelov 2014) where hypolithic communities (on the underside of rocks) contribute to biogeochemical processes (Mergelov et al. 2020), or at seabird colonies where organic matter accumulates to form ornithogenic soils (Bowman et al. 1996). Ornithogenic soils can be hundreds to thousands of years old (Emslie et al. 2014).

Antarctic soils are different from those found on other continents and were added as Gelisols to the United States soil classification system in 1997. Characteristics include (Fisher 2014):

- limited free water
- at times, high salt concentration
- nutrient deficiencies (oligotrophic)
- a thick layer of permafrost
- high ultraviolet radiation in summer that sterilises the surface
- strong winds continuously eroding the landscape.

Antarctic soils are often highly oligotrophic – that is, they lack, or have only low levels of, important nutrients, such as phosphates, nitrates, iron and carbon (Arenz et al. 2014). Soils in different regions also have different properties and characteristics because of differences in environmental conditions in the various parts of the continent (Campbell & Claridge 2009).

Antarctic soils contain diverse and abundant terrestrial biodiversity, comprising microbial communities of bacteria, archaea, dinoflagellates, viruses and algae. The level of endemism is high in these diverse communities – that is, many species are found nowhere else (Hughes et al. 2015). Some Antarctic microbial communities appear to have existed for millions of years. Throughout several glacial cycles, the isolation of areas for very long periods resulted in evolutionary isolation and, hence, distinct bioregions (Convey et al. 2008).

Despite the important roles of Antarctic terrestrial microbial communities, detailed knowledge about them is still relatively limited. Application of new research techniques is enabling documentation of the high levels of diversity of local communities and the complexities of microbial assemblages at different sites.

Although once considered a sterile environment, Antarctica harbours a great variety of bacteria and archaea – microorganisms that often inhabit extreme environments. New species are still being discovered – see, for example, Peeters et al. (2011). Their taxonomy is complex because a large number of new lineages have been identified, and taxonomic affiliations are difficult to resolve (Lambrechts et al. 2019). Microbial biomass comprises a significant part of the total Antarctic biomass. A study in the Dry Valleys, Ross Sea region, determined that cell numbers in the mineral soils were more than 4 orders of magnitude higher than previously thought (3–40 million cells per gram wet weight) (Cowan et al. 2002). Microbial communities are highly diverse and heterogeneous in different environments characterised by, for example, variations in soil pH, level of disturbance and proximity of seabird colonies or seal wallows (Chong et al. 2010).

A recent study suggested that some Antarctic soil microbes may source their carbon and energy from atmospheric hydrogen, carbon dioxide and carbon monoxide. Since samples collected at Robinson Ridge, near Casey Station, and Adams Flat, near Davis Station, provided the same results, it may indicate that this so-called trace gas scavenging is a widespread mechanism in Antarctica's soils (Ji et al. 2017).

Soil microorganisms affect the weathering of rocks, control soil development and play a major role in nutrient cycling. However, microbial habitats are not well presented in the current estate of protected areas in Antarctica; there is little to no protection of their habitats because they are not visible and often not considered in environmental impact assessments (Hughes et al. 2015).

Climate change puts soil communities at risk, and may alter species abundance and food-web complexities in ways not yet fully understood (Andriuzzi et al. 2018).

Human activities are a major threat to soil organisms. Buildings and roads can compact soils and change the way water flows, and chemical spills and waste disposal impact microbial habitats. Genetic contamination of microorganisms occurs through clothing fibres, equipment, dust, and human skin cells and waste (Sjöling & Cowan 2000, Takashima et al. 2004, Teufel et al. 2010). This may affect the value of the Antarctic microbiome with regard to bioprospecting. Non-native microorganisms introduced to the environment by humans may alter community structure, function and genetic diversity, and eventually lead to the loss of the native soil communities (Hughes et al. 2015).

Antarctic plants

Plant life on the Antarctic continent is limited (Andriuzzi et al. 2018). There are no trees, and the only 2 native flowering (vascular) plants – *Deschampsia antarctica* (a grass) and *Colobanthus quitensis* (a cushion plant) – are limited to the northern part of the Antarctic Peninsula (Convey 1996). Plants with root systems do not grow in the soils of East Antarctica (Kudinova et al. 2015). Plants comprising mainly microflora, such as lichens and mosses, dominate the few ice-free areas, and algae prosper under rocks and in snowfields where there is sufficient moisture. In maritime Antarctica, which includes the South Sandwich and South Shetland islands, and the western Antarctic Peninsula, more than 200 species of lichens and more than 100 species of mosses occur, while in continental Antarctica 92 lichens and 25 mosses occur (King 2017).

Environmental factors that affect plants' growth and ability to survive are freezing temperatures, lack of water and extremely strong winds. However, in summer, temperatures of soil and plant surfaces can be much higher than air temperatures recorded about 2 m above, providing favourable microclimates for growth. Antarctic moss and lichen beds are the forests of Antarctica (Kennedy 1993), offering vital habitats for terrestrial invertebrates and microorganisms (Prather et al. 2019). Since both mosses and lichens depend on ice-free habitat, their distribution is highly fragmented in the mosaic of ice-free areas.

As one of the most successful groups of organisms on Earth, lichens occur worldwide in many different habitats (hot and cold deserts, coastal areas, and high mountains) (Singh et al. 2018). With more than 400 species, lichens are the most successful plants in Antarctica (Pugh & Convey 2008). On the Antarctica Peninsula, there are 269 known species of lichens and 134 species of mosses, compared with 92 lichen and 25 moss species in continental Antarctica. In the subantarctic, there are more than 250 lichen and 335 moss species plus 60 species of flowering plants (King 2017).

Plant diversity decreases with increasing latitude. Whereas there are about 350 lichen species in the northern parts of the Antarctic Peninsula, there are only about 12 species at 87°S (Sancho et al. 2019). Lichens are more widespread and able to occupy drier sites than mosses. They grow slowly and can exist for hundreds of years (Bergstrom et al. 2021). The diversity and growth rates of lichens appear to be sensitive to changes in mean annual temperatures. Lichen observations, in conjunction with molecular studies, may enable researchers to use them as biomonitors of changes in the environment (Sancho et al. 2019).

Mosses have unique survival strategies that enable them to live in cold conditions, such as a high tolerance to desiccation and the capacity to cease all metabolic activities (Turnbull et al. 2009, Cannone et al. 2017). The summer is the growth season of mosses, when the sun frequently shines for 24 hours per day and ambient temperatures are near or above 0 °C. During their growing season, moss beds need free water; therefore, water availability and temperature largely determine their distribution. Mosses often thrive near melt lakes and other areas where free water becomes available in summer, when melting snow and ice produce temporary lakes and streams. Where conditions are favourable, and especially where weathered nutrients are available from ancient penguin colonies (Wasley et al. 2012, Emslie et al. 2014), lush moss beds occur, such as those found in the Windmill Islands region.

The moss growth season lasts only 8–16 weeks (Robinson et al. 2018, Singh et al. 2018).

Antarctic mosses grow less than 6 mm per year – much slower than mosses in temperate conditions (Bramley-Alves et al. 2015). Under optimal conditions, moss turfs can reach a thickness of up to 14 cm; individual plants can live for more than 100 years (Clarke et al. 2012, Amesbury et al. 2017). Many moss species photosynthesise optimally when surface temperatures are around 15 °C or above (Lewis Smith 1999). Thus, although Antarctic mosses live in a cold environment, their photosynthetic capacity is geared towards much higher temperatures (19–26.3 °C), similar to temperate or tropical species. They survive by reducing respiration at low temperatures in winter, when they metabolically shut down into a state of dormancy (Perera-Castro et al. 2020).

Mosses occupy the most extensive vegetated areas on the Antarctic continent, but the species composition of mosses is changing, and, in some areas (Robinson et al. 2018), their abundance is decreasing. Reductions in moss beds mean loss of habitat for associated microinvertebrates. Furthermore, construction of new infrastructure may affect moss beds regionally through pollution (Bergstrom et al. 2021).

There is a complex relationship between the amount of free water available to moss beds through increased melt and moss bed growth. Natural drainage patterns can be altered when infrastructure is built, at times with ongoing effects. In addition, trampling of the vegetation, dust from vehicle traffic, and dumping of gravel and snow onto moss beds have negative effects (Bergstrom et al. 2021). Furthermore, warmer temperatures and increased water availability may enable non-native species to establish (see Non-native species). These changes require monitoring through long-term field-based programs.

Snow algae turn the snow cover green or red when they bloom in the summer (Davey et al. 2019, Khan et al. 2021). At the South Shetland Islands, Antarctic Peninsula, bloom areas ranged from 300 to 145,000 m^2. The largest blooms occur on relatively shallow slopes and near colonies of seabirds or seals whose presence adds nutrients to the environment. Many algal species are not yet identified, and little is known about their dispersal mechanisms. If suitable dispersal mechanisms exist, the coverage of snow algae may increase as the peninsula warms, as long as nutrient sources are available. Snow algae may become an important terrestrial sink for carbon (Gray et al. 2020).

Climate change is likely to drive some marked changes in the Antarctic flora. For example, in the Antarctic Peninsula region, moss banks have responded rapidly to the gradual increase in temperature with increased growth rates (Amesbury et al. 2017). As temperatures rise, ice-free areas will increase (Lee et al. 2017), enabling increased colonisation (both locally and over long distances). Certain local populations are likely to expand, and their biomass will increase (Singh et al. 2018). However, the availability of free water is another important factor, and the responses to environmental change will be species-specific. For example, where water availability decreases, the abundance of submergence-tolerant species decreases, while desiccation-tolerant species become more abundant. This has already been observed in the Windmill Islands, East Antarctica (Robinson et al. 2018, Bergstrom et al. 2021).

Subantarctic plants

At Australia's subantarctic islands, the vegetation is more diverse than on the Antarctic continent. Macquarie Island supports 91 species of moss, many lichens and liverworts, and 47 species of vascular plants, of which 4 are endemic (Selkirk et al. 1990). Three of these endemic species are listed as threatened. One is the Macquarie cushion plant (*Azorella macquariensis*), a keystone species of the extensive feldmark vegetation (patchy, low-growing vegetation intermixed with barren, gravelly substrate). Macquarie Island supports by far the largest and best examples of feldmark vegetation in Australia. The Macquarie cushion plant, one of the species of the feldmark, has suffered a catastrophic population collapse triggered by climate change, which is expected to permanently alter this alpine ecosystem. Since 2009, dieback has affected up to 90% of the cushion plants in some locations. The cause of the dieback has been attributed to the alteration of soil conditions related to climate change, and potentially an unidentified pathogen (Skotnicki et al. 2009, Dickson et al. 2019, Dickson et al. 2021).

Macquarie Island is the most southerly location in the world for naturally occurring orchids. Two species of orchids are endemic to the island; both are tuberous, deciduous orchids less than 5 cm tall, and both are listed as critically endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). The grooved helmet-orchid (*Corybas sulcatus*) forms loose colonies about 80–150 m above sea level. Only 4 locations, which cover less than 0.3 ha, are known for this species on the eastern side of the island's plateau (Skotnicki et al. 2009). The windswept helmet-orchid (*Corybas dienemus*) occurs mainly at the northern end of the island, usually less than 30 m above sea level in waterlogged peat or beneath the megaherb *Stilbocarpa polaris* (Copson 1984). Its area of occupancy covers about 1.5 ha. The distributions of both species are disjunct and fragmented, and much of their habitats were lost due to grazing and burrowing by European rabbits (*Oryctolagus cuniculus*). Since the rabbits were eliminated, the cover of native grasses, such as *Agrostis magellanica* and *Deschampsia chapmanii*, has increased (Fitzgerald et al. 2021). The megaherbs Macquarie Island cabbage (*Stilbocarpa polaris*) and silver-leaf daisy (*Pleurophyllum hookeri*), as well as tussock grass (*Poa foliosa*), have also recovered substantially. Thus, aside from the cushion plant dieback, the vegetation of Macquarie Island is improving significantly since the eradication of rabbits and rodents in 2011, and grazing and other impacts have ceased (Springer 2018). Overall, the vegetation of the island is in the best shape it has been for more than a century (Visoiu 2019).

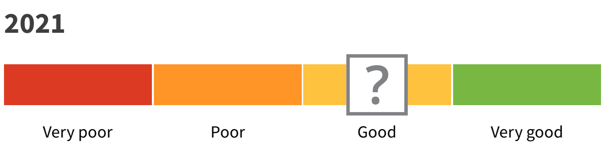
Macquarie Island is a World Heritage Area because of its unique exposed oceanic crust, and its wild, natural beauty. With less than 9% of the plant species being introduced weed species (4 extant species), Macquarie Island has likely the most natural floral assemblages of any island in the subantarctic. However, a European native and worldwide weed, the annual blue grass (*Poa annua*) is the most widespread plant invader in the subantarctic and the world's most widely distributed species (Chwedorzewska 2008). It is now well established at Australia's 2 subantarctic World Heritage sites, Heard Island and McDonald Islands, and Macquarie Island (Williams et al. 2018). At Macquarie Island, annual blue grass is perennial and able to survive the winter. It grows quickly when the short growing season commences, enabling it to compete with native plants (Williams et al. 2018).

In the 2013–14 summer, small patches of 2 non-native grass species (*Agrostis stolonifera* and *A. capillaris*) were discovered at Macquarie Island. The plants had not yet produced flowers, and because of their limited extent they were removed. Human activities may have inadvertently introduced seeds, but natural transport (e.g. by birds) cannot be excluded (Pertierra et al. 2016).

The vegetation of Heard Island covers the ice-free areas and includes vascular plants (12 species), mosses (44 species), lichens

(34 species) and liverworts (17 species) (Hughes 1987, Bergstrom et al. 2002). Heard Island and McDonald Islands became a World Heritage Area because of their unique wilderness, which provides examples of biological and physical processes that occur in an environment undisturbed by humans. As the glaciers are retreating, new habitat becomes available for *Poa annua*, an invasive grass. The extent of this non-native invader at Heard Island is currently unknown, but it had spread substantially by 2003. In the 2003–04 summer, a single specimen of a small daisy (*Leptinella plumosa*) occurred at Heard Island where it had previously not been found (Frenot et al. 2005)

Assessment Terrestrial species



Adequate confidence

Macquarie island vegetation is recovering, but Antarctic mosses are deteriorating.

Assessment Macquarie Island vegetation

Adequate confidence

Since the eradication of rodents and rabbits, the island's vegetation is overall making a notable recovery. Macquarie cushion plants and many bryophyte species are still suffering some dieback.

Assessment Antarctic mosses

2021

Adequate confidence

Species composition is changing. Increasing mortality causes reduction of abundance in extensively vegetated areas. Loss of habitat for associated microinvertebrates. Some lichen habitat is expanding. Continued loss of moss banks and associated habitat.

Marine vertebrate species

Biodiversity of vertebrates in Antarctic waters is relatively low in comparison with mid-latitudinal or tropical ecosystems, but many species are highly abundant. Fish are the most diverse vertebrate group, with around 200 species, followed by flying seabirds (7 species on the continent and 13 on subantarctic islands) and penguins (2 species in East Antarctica, a further 3 on the Antarctic Peninsula, and 5 on subantarctic islands). Ice-breeding seals (4 species), fur seals (3 species), sea lions (1 species) and elephant seals (1 species) are also part of the Antarctic fauna. In addition, more than 30 species of baleen and toothed whales forage in the Southern Ocean, and some species of toothed whales appear to remain there throughout the year. The Southern Ocean is home to the largest community of warm-blooded (endothermic) predators in the world (Krause et al. 2020).

Status and trend data are available for only a few species (Tables 2, 3 and 4) – notably, the 2 penguin species on the continent, the giant petrel population, some albatross populations, and fur and elephant seal populations 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. Visits to Heard Island and McDonald Islands are infrequent; thus, recent data are lacking. Note that the listing of species frequently varies between national and international assessments, because species are assessed at different scales.

Flying seabirds

Globally, among the 359 seabird species are 22 species of albatrosses, 52 species of petrels and 18 species of penguins (see Penguins). Of the 46 flying seabird species that occur in the Antarctic region, 7 live in the high latitudes (Barbraud & Weimerskirch 2006), while the remainder inhabit subantarctic islands (Woehler & Croxall 1997). High-latitude species include snow petrels (*Pagodroma nivea*), southern fulmars (*Fulmarus glacialoides*) and Wilson's storm petrel (*Oceanites oceanicus*). Albatrosses, diving petrels, cormorants, shearwaters and other species live in the subantarctic, but may visit Antarctic waters when foraging.

Some 31% of all seabirds (110 species) are globally threatened, including all but one species of albatross, and another 11%

(40 species) are listed as Near Threatened (Dias et al. 2019). The biggest threats are invasive, non-native species; bycatch in fisheries; overfishing; and climate change. Of the 22 albatross species, 21 are listed on the International Union for Conservation of Nature (IUCN) Red List. The only albatross listed with a status of Least Concern is the black-browed albatross (*Thalassarche melanophris*), whose global population appears to be increasing (BirdLife International 2018). All albatross species plus 7 petrel species are covered under the Agreement on the Conservation of Albatrosses and Petrels (ACAP 2021a).

Seabirds typically live for several decades; they mature late and lay only 1 or 2 eggs per year, which usually do not get replaced when lost. Some albatross species breed only every second or sometimes third year. Adult survival is usually very high, and many adults return the following year to their colonies. Because of their low annual reproductive output, seabird populations are unable to withstand even small increases in their natural mortality rates. Since most Antarctic seabird species require bare rock as breeding habitat, the ice-free areas are important for their survival. Consequently, many species breed close to each other, often in very large colonies.

Antarctic terrestrial ecosystems rely largely on nutrients derived from the ocean. Because of their large populations, seabirds play a major role in the transport of marine organic matter onto land, especially during the breeding season. Seabirds deposit large quantities of guano at their colonies and with it carbon, nitrogen and metals, such as zinc and copper. Thus, seabird activities enable biotransportation of trace elements from the marine to the terrestrial environment, and enrich the soils (Castro et al. 2021).

Since many seabird colonies are remote and difficult to access, surveys of most Antarctic seabird populations occur only infrequently, if at all. Furthermore, crevice-breeding birds display cryptic behaviours (an ability to avoid observation or detection) during the breeding season, making it very challenging to obtain population estimates.

The species diversity on the subantarctic islands is different from that on or near the Antarctic continent. The fauna of Heard Island and McDonald Islands includes 4 species of penguin not found on the continent, and 15 species of flying seabirds, including 2 species of albatross, several petrels and skuas (*Stercocarius* spp.), and the black-faced sheathbill (*Chionis minor*). Because the islands support various threatened and endangered seabird species, the IUCN has declared them an Important Bird Area. Heard Island is the largest subantarctic island that is free from introduced vertebrate species (Birds Australia 2010).

In 2011, the IUCN also nominated Macquarie Island as an Important Bird Area because of the presence of various threatened and endangered seabird species (BirdLife Australia 2021). Macquarie Island is home to an estimated 3.5 million seabirds, comprising 13 distinct species. These include 4 species of penguins, a variety of small petrels and 4 albatross species: wandering (*Diomedea exulans*), grey-headed (*Thalassarche chrysostoma*), light-mantled (*Phoebetria palpebrata*) and black-browed. Three species of albatross are either increasing (black-browed and light-mantled) or stable (grey-headed). The extremely small breeding population of wandering albatross (5–10 breeding pairs) has been decreasing in the past decade (Cleeland 2018). Globally, the species is listed as Vulnerable, based on relative trends in numbers and survival rates in the past, similar to those observed in the Indian Ocean populations. Longline fisheries elsewhere still pose a risk to some albatross species and grey petrels (*Procellaria cinerea*), but risks off Macquarie Island have decreased as a result of careful management of fishing activities. The numbers of grey petrels and soft-plumaged petrels (*Pterodroma mollis*) have increased since the eradication of introduced predators and rodents (McInnes et al. 2019). At Macquarie Island, the successful eradication of rabbits and rodents in 2011 also enabled the recovery of several petrel species (e.g. Antarctic prions – *Pachyptila desolata*, and white-headed petrels – *Pterodroma lessonii*), and the recolonisation of others (e.g. blue petrels – *Halobaena caerulea*, and grey petrels) (Bird et al. 2021). The presence of burrowing petrel species is particularly difficult to detect, but application of genetic techniques (see case study: DNA technology applied in seabird research) has allowed identification of 8 of the 9 petrel species that used to breed on the island (McInnes et al. 2019).

Commercial fishing operations are one of the most serious threats to seabirds, particularly those breeding at lower latitudes on the subantarctic islands. Within the Australian jurisdiction, incidental seabird mortality is strictly controlled and regulated, and is relatively low. However, seabirds fly enormous distances and often forage in the high seas in international waters, where they interact with longline fisheries and net fisheries. Seabirds can become caught when they scavenge for food behind longline fishing vessels; as the line sinks, they drown. Seabird mortalities can also occur from entanglement in nets, or cable strikes in trawl fisheries. Particularly through the efforts of the Agreement on the Conservation of Albatrosses and Petrels (ACAP 2021a), there is progress in developing and improving best practices and procedures for minimising seabird deaths in fisheries. For example, after the introduction of compulsory line weighting in longline fleet fishing in the Convention on the Conservation of Antarctic Marine Living Resources Area, seabird bycatch in that area is at historically low levels.

Other efforts include improvements in line weighting in longline fisheries, development of underwater bait-setting devices (which deliver baited hooks out of reach of most diving seabirds) and implementation of new, highly effective, modern techniques to avoid bycatch in trawl fisheries.

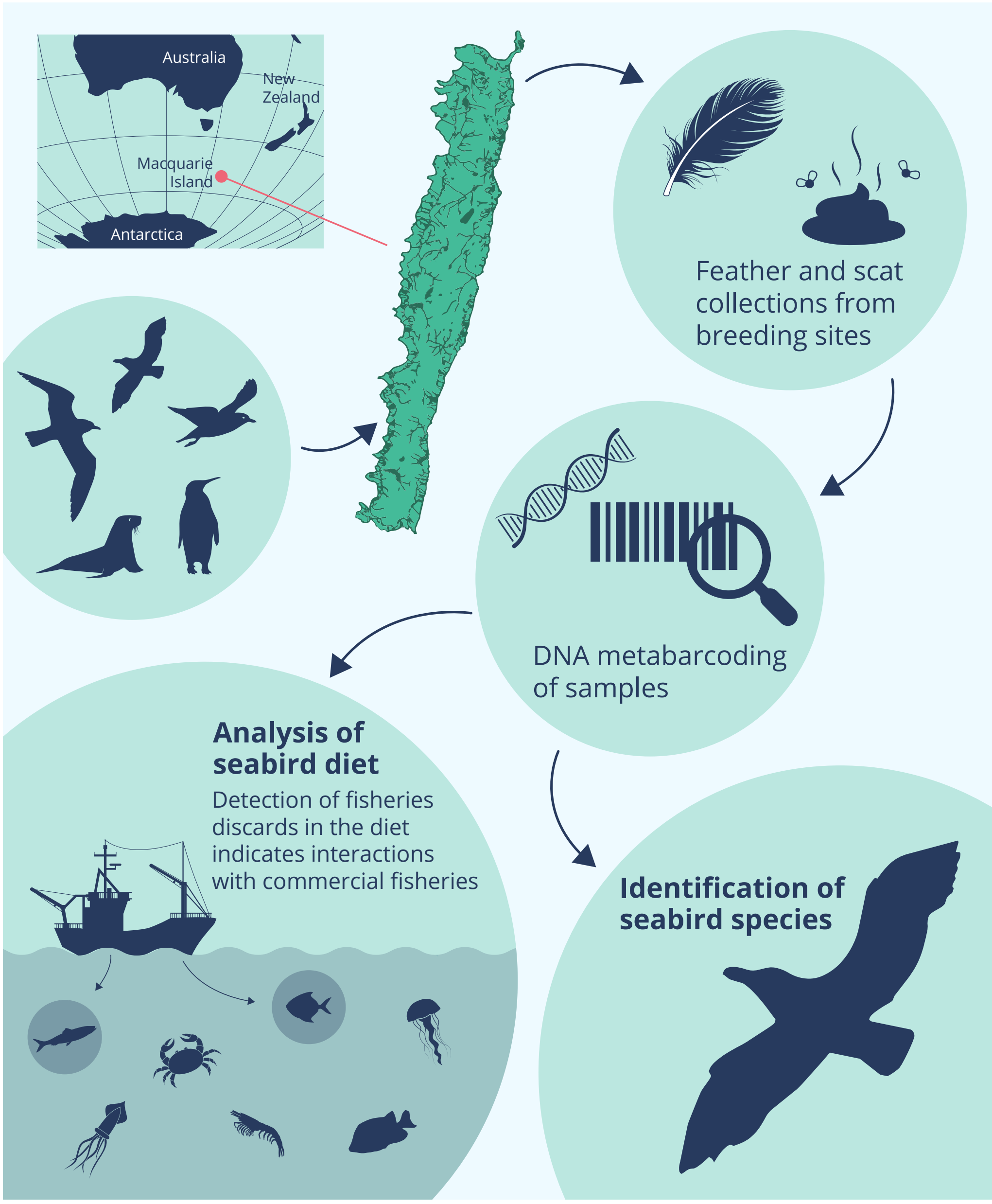
One of these techniques is DNA metabarcoding (see case study: DNA technology applied in seabird research). Not every seabird species is inclined to follow fishing vessels. To determine which species are at most risk, DNA metabarcoding has been used to identify the prey ingested by seabirds and compare the results with the target species caught by commercial fisheries near the breeding colonies (McInnes et al. 2017); see case study: DNA technology applied in seabird research).

On land, flying seabirds may experience disturbance by humans, loss of breeding habitat, increased competition for nest sites, and increased exposure to parasites and pathogens. On subantarctic islands, predation by non-native predators, such as cats, rats and mice, has reduced their breeding success. Introduced predators pose a key threat, because they can increase the mortality of adult birds, and reduce breeding success when chicks fall victim to predators. At Macquarie Island, cats (*Felis catus*) were eradicated in 1998–2000 (Robinson & Copson 2014). Heard Island and McDonald Islands have so far remained free from introduced vertebrates. Introduced species such as rabbits can also have an indirect effect when overgrazing leads to destabilisation of the substratum, which can lead to an increase in landslides across breeding areas (Scott & Kirkpatrick 2008, Bird et al. 2021).

Case study DNA technology applied in seabird research

Seabirds make a living in the world's vast oceans. As a result of their highly developed sense of smell, albatrosses and petrels can detect potential food sources over large distances by navigating through an 'olfactory landscape'. A change in an olfactory feature may provide the cue to a seabird that it has reached its foraging destination (Nevitt 2000, Nevitt 2008). Crushed prey, such as krill, squid and fish, release certain scents (e.g. aromatic organic compounds such as pyrazines) that seabirds are able to detect. For this reason, seabirds may be attracted to fishing vessels, where they prey on discards, bait or fish lost in the fishing operation. Thus, foraging areas of seabirds and fishing grounds of commercial operators may overlap, exposing the birds to the risk of incidental mortality through interactions with fishing gear. Since the way seabirds interact with fisheries varies among species, the question arises: for which seabird species do commercial fisheries pose a risk?

To answer this question, a method called DNA metabarcoding has been employed. This technique enables the identification of multiple taxa (groups of animals) in one sample (Figure 9). Researchers collect samples of seabird scats at their colonies, and extract remaining genetic material (DNA) of the ingested prey. By comparing the samples with the DNA of known marine species, researchers can determine the diet composition of individuals or groups.



Note: DNA was extracted from scats of many different predators. 1. Through DNA metabarcoding, the prey species ingested by predators were identified and compared to species caught by commercial fishing vessels. 2. DNA metabarcoding can also be used to identify seabird species to detect whether they have returned to a previously occupied breeding island.
Source: Julie McInnes

Figure 9 DNA metabarcoding

A DNA metabarcoding study on Tasmania's shy albatross (*Thalassarche cauta*; Figure 10) showed that most birds captured their prey naturally, rather than eating fish captured by commercial fishers. However, at times a quarter of the population was consuming fisheries discards. Albatross foraging areas overlapped with commercial fishing operations in 6 Commonwealth fisheries in south-eastern Australia. The level of probable engagement of these albatrosses with fishing vessels varied with season, and was consistently high during the brood period (McInnes et al. 2021).

These examples show the versatility of DNA metabarcoding in the study of seabirds. This noninvasive technique provides valuable insights into seabird ecology, and offers an effective tool for wildlife and fisheries managers (McInnes et al. 2017).

Photo: Julie McInnes

Figure 10 Colony of shy albatrosses at Albatross Island, Tasmania

A different use of DNA metabarcoding is the identification of burrowing petrels. At Macquarie Island, at least 9 species of burrowing petrels were abundant before non-native predators were introduced. Cats preyed on chicks, and rats consumed eggs and perhaps small chicks. Thousands of rabbits overgrazed large areas of the island; this led to erosion and eventually loss of habitat of burrowing petrels.

After the eradication of the introduced species, feathers and scats were collected across the island to determine which species were present in the recovering ecosystem. Directly accessing burrows to identify petrel species causes disturbance, and the burrows are sometimes deep enough for their occupants to be out of reach. Using DNA metabarcoding on shed feathers and scats collected at burrow entrances confirmed the return of 8 different petrel species to the island, including the difficult-to-detect soft-plumaged petrel (*Pterodroma mollis*) and fairy prions (*Pachyptila turtur*) (McInnes et al. 2021).

Photo: Julie McInnes

Figure 11 Sooty shearwater (*Ardenna grisea*), one of the species identified by DNA metabarcoding

Although removal of invasive introduced vertebrates was important for the avian biodiversity on Macquarie Island, the effects on native predator populations must be taken into consideration (Travers et al. 2021). The eradication efforts negatively affected top-order predators; 762 giant petrels (*Macronectes* spp.) and 512 brown skuas (*Stercorarius antarcticus lonnbergi*) died of secondary poisoning when they scavenged on rabbit and rodent carcases. Furthermore, an important food source disappeared with the eradication because these predatory birds used to feed on rabbits. However, at the population level, these losses were not considered a threat to the viability of the affected populations (Springer & Carmichael 2012).

With regard to endangered species, Australia has threat abatement plans that define actions to be undertaken to reduce the impacts of threats to levels where populations of listed species are no longer threatened (DEE 2018). The *Threat abatement plan for the incidental catch (or bycatch) of seabirds during oceanic longline fishing operations* (2018) deals specifically with key threatening processes in these fisheries, and stipulates required research and management actions. Under the EPBC Act, Australia has also formulated a national strategy for the protection of threatened albatross and petrel species. At the time of writing, the *National recovery plan for albatrosses and petrels 2021* (the third such plan) was open for public comment until 27 August 2021; it is anticipated to be finalised in early 2022 (DAWE 2021a).

Penguins

Penguins are estimated to comprise about 90% of the biomass of seabirds in Antarctica (Bargagli 2005), but, as noted above, populations may be difficult to assess accurately. Like all seabirds, they are long-lived and produce only 1 or 2 eggs per year. They often inhabit large colonies in the coastal areas of Antarctica and subantarctic 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. This can increase their vulnerability to localised prey depletion through commercial fishing. Of the 18 species in the penguin family, 7 live and breed in the Australian Antarctic Territory and Macquarie Island, but only emperor (*Aptenodytes forsteri*) and Adélie (*Pygoscelis adeliae*) penguins inhabit large colonies in East Antarctica; fewer than 30 pairs of chinstrap penguins (*P. antarctica*) occur at the Balleny Islands (Macdonald et al. 2002). Adélie penguins spend the winter months at sea and return to their breeding colonies during the summer, whereas emperor penguins breed during the winter months and fledge their young in summer.

Recent surveys show that the total population of Adélie penguins in East Antarctica has increased by 69% over 30 years, from about 520,000 to approximately 878,300 breeding pairs (Southwell et al. 2015b, Southwell et al. 2015a). However, the increase did not occur in all surveyed populations. For example, at the Scullin and Murray monoliths, Adélie penguin populations appear to have remained stable or decreased somewhat (Southwell & Emmerson 2019). Populations elsewhere – for example, on the Antarctic Peninsula – had significantly decreased over 50 years (Dunn et al. 2016).

Emperor penguin colonies are largely located on the land-fast sea ice near the coast of Antarctica. Many colonies are remote from research stations, making estimations of their size challenging. Long-term population data are available for only a few colonies. In 2009, a satellite-based synoptic survey attempted to estimate the size of the global population of emperor penguins, excluding nonbreeders and juveniles (Fretwell et al. 2012) (see case study: Satellite technology reveals more than the distribution of emperor penguins). A major caveat is that very high-resolution satellite imagery is only available late in the breeding season of these penguins, when both partners of a breeding pair are hunting food for their offspring. This can lead to significant underestimates of the size of the breeding population.

The future of emperor penguins depends on the extent to which Earth warms in the coming decades. If global temperature rise can be limited to 1.5 °C, about one-third of the global emperor penguin population will be lost, and two-thirds of the currently existing colonies will be quasi-extinct. If the temperature increases by 4 °C, some 92% of the current population will no longer exist, and 9 of 10 colonies will be quasi-extinct. Major forces driving these changes are loss of sea ice and increased frequency of extreme events (Jenouvrier et al. 2021).

The greatest threats for penguins in East Antarctica are likely to be loss of breeding habitat (in the case of emperor penguins), a reduction in food availability because of climate change or potentially the resumption of the krill fishery, and habitat loss (Trathan et al. 2015). Precautionary catch limits for krill amount to 2.53 million tonnes (t) in the area 30°E to 80°E, and a further 440,000 t from 80°E to around 150°E (Nicol et al. 2012). Any increase in human activities in the area has the potential to disturb wildlife if not managed carefully (Brooks et al. 2019). Changes in sea ice conditions have varied consequences. For example, a reduction in the land-fast sea ice extent could shorten foraging distances, but a reduction in pack ice would reduce krill production (Bretagnolle & Gillis 2010). It is difficult to predict the extent to which 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 and other long-lived species.

The subantarctic Heard and Macquarie islands are rare areas of terrestrial 'real estate' in the Southern Ocean. King (*Aptenodytes patagonicus*), gentoo (*Pygoscelis papua*) and southern rockhopper (*Eudyptes chrysocome*) penguins occur in both locations, while royal penguins (*E. schlegeli*) are found only on Macquarie Island, and macaroni penguins (*E. chrysolophus*) occupy Heard Island and other subantarctic islands. These islands are critically important breeding areas for these species. The most recent published estimate of the breeding population of royal penguins is 750,000 pairs in 2016 (Salton et al. 2019).

A recent study examined the phylogeographic structure of the *Eudyptes* species, and questioned the classification of royal and macaroni penguins as separate species due to the lack of significant genetic and phylogeographic structure. However, the authors stated that their findings were not fully conclusive and that further investigations are required. The same study confirmed the separation of rockhopper penguins into 3 species (Frugone et al. 2018).

The most recent census of gentoo penguins on Macquarie Island in 2017 recorded the fewest breeding pairs since counts began, with 2,527 ± 66 pairs in total. Island-wide, breeding pairs have decreased by 1.8 ± 0.4% per year over the past 34 years (Pascoe et al. 2020). Macquarie Island remains an important site for many penguin species, including king and southern rockhopper penguins.

Table 2 National (EPBC Act) and international (IUCN) status of threatened flying seabirds and penguins breeding in Australia's jurisdiction

Order	Species	EPBC Act	IUCN (global population assessment)
Procellariiformes	*Macronectes giganteus* – southern giant petrel	Endangered	Least Concern Increasing
	Macronectes halli – northern giant petrel	Vulnerable	Least Concern Increasing
	Diomedea exulans – wandering albatross	Vulnerable	Vulnerable Decreasing
	Phoebetria palpebrata – light-mantled sooty albatross	Not listed	Near Threatened Decreasing
	Thalassarche cauta – shy albatross	Endangered	Near Threatened Unknown
	Thalassarche chrysostoma – grey-headed albatross	Endangered	Endangered Decreasing
	Thalassarche melanophris – black-browed albatross	Vulnerable	Least Concern Increasing
Sphenisciformes	*Aptenodytes forsteri* – emperor penguin	Not listed	Near Threatened Decreasing
	Aptenodytes patagonicus – king penguin	Not listed	Least Concern Increasing
	Eudyptes chrysocome – southern rockhopper penguin	Not listed	Vulnerable Decreasing
	Eudyptes chrysolophus – macaroni penguin	Not listed	Vulnerable Decreasing
	Eudyptes schlegeli – royal penguin	Not listed	Near Threatened Stable
	Pygoscelis adeliae – Adélie penguin	Not listed	Least Concern Increasing
	Pygoscelis papua – gentoo penguin	Not listed	Least Concern Stable

EPBC Act = *Environment Protection and Biodiversity Conservation Act 1999*; IUCN = International Union for Conservation of Nature
Source: IUCN (2021)

Case study Satellite technology reveals more than the distribution of emperor penguins

Emperor penguins are an iconic Antarctic species, and the only vertebrate that breeds throughout the winter. The first emperor penguin colony was discovered in the southern Ross Sea in 1901. By 2010, 32 others had been located, although the continued existence of some was uncertain (Wienecke 2009, Wienecke 2010).

The first synoptic survey of this species used satellite imagery to examine the entire coast of Antarctica, and confirmed and discovered new colonies, bringing the total to 46 (Fretwell et al. 2012). By 2019, this number had increased to 54, of which 50 still existed; in 2020, a further 8 small colonies were found (Fretwell & Trathan 2019). There are now 22 confirmed emperor penguin colonies in the Australian Antarctic Territory.

Researchers visiting the West Antarctic Ice Shelf (68.63°S, 77.97°E) in December 2009 recorded for the first time an emperor penguin colony on top of an ice shelf (Wienecke 2012) (Figure 12). Subsequently, satellite imagery enabled observations of changing locations of some emperor penguin colonies. Four had also relocated onto ice shelves in years when the sea ice conditions were poor (Fretwell et al. 2014).

Satellite imagery enables observations relating to changes in sea ice conditions and emperor penguin breeding success. For example, 10 years of remote observation documented significant variation in the second largest colony at Halley Bay, West Antarctica. From 2016 to 2018, this colony experienced near-complete breeding failure in 3 consecutive years due to low sea ice extent and early sea ice breakout at a time when the penguin chicks were far from fledging. Since 2015, the population size at the Dawson–Lambton colony, 55 km from Halley Bay, has increased massively (1000%); this may indicate that the penguins from Halley Bay relocated to the Dawson–Lambert colony (Fretwell & Trathan 2019).

Early ice breakup also led to the demise of large numbers of emperor penguin chicks at Cape Crozier (77.5°S, 169.3°E) in the Ross Sea, one of the two most southerly emperor penguin colonies (Figure 13). Increasing wind speeds and increasing temperatures appear to have contributed to this event (Schmidt & Ballard 2020).

a

b

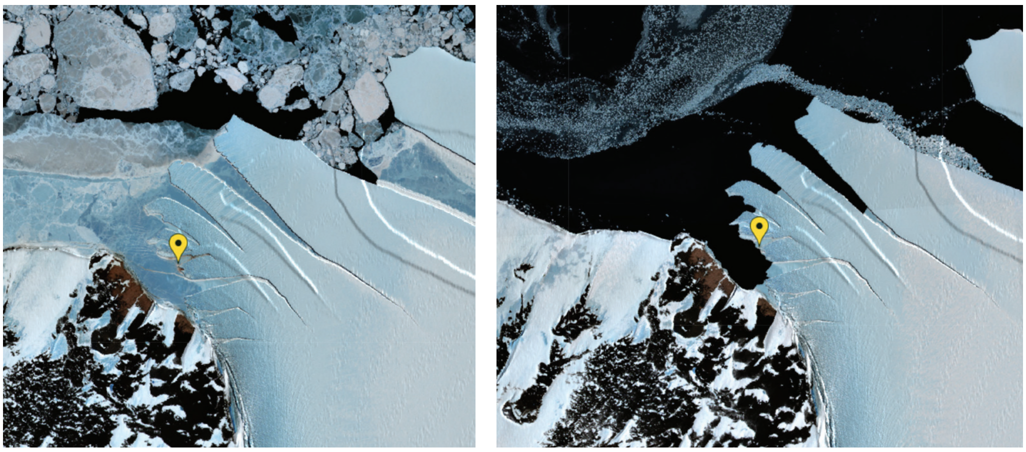
Photos: Barbara Wienecke

Figure 12 Emperor penguins on top of the West Antarctic Ice Shelf, December 2009

Because of their critical dependence on sea ice, emperor penguins are particularly vulnerable to the effects of climate change (Trathan et al. 2020). Although use of satellite imagery is vital for continent-wide observations of the impact of variations in sea ice conditions on this species, ground visits are still necessary to obtain reliable estimates of population sizes.

a

b



(a) 24 November 2018; the edge of the fast ice is about 2 km from the colony (yellow marker).
(b) 5 December 2018; a severe storm on 4 December blew out the fast ice. Many chicks were caught out on 2 large ice floes that subsequently disappeared.
Images: Sentinel2, European Space Agency. Contains modified Copernicus Sentinel data (2021), processed by Sentinel Hub.

Figure 13 Emperor penguin colony at Cape Crozier, southern Ross Sea

Seals (Pinnipedia)

Both true seals and eared seals inhabit the Antarctic region and are assessed under the EPBC Act and by the IUCN (Table 3).

True seals (Phocidae)

The Antarctic pack ice zone may be the home of about 50% of the world's true seal populations. Three species of seals inhabit the pack ice zone that surrounds Antarctica: crabeater (*Lobodon carcinophaga*), leopard (*Hydrurga leptonyx*) and Ross (*Ommatophoca rossii*) seals. They rely on the sea ice at critical stages of their lives, particularly in their reproductive and moulting periods. Their populations are difficult to study because these seals are highly mobile, disperse across large and inaccessible regions, and spend long periods foraging in the ocean. Some species also do not appear to occupy set territories. Sightings are usually of individuals or very small groups. Surveys to estimate population sizes are infrequent, because the studies are expensive and labour-intensive. Consequently, population trends are largely unavailable.

Table 3 National (EPBC Act) and international (IUCN) status of seals in Australia's jurisdiction

Family	Species	EPBC Act	IUCN – global population trend
Phocidae (true seals)	*Hydrurga leptonyx* – leopard seal	Marine	Least Concern Unknown
	Mirounga leonina – southern elephant seal	Vulnerable	Least Concern Stable
	Leptonychotes weddellii – Weddell seal	Marine	Least Concern Unknown
	Lobodon carcinophaga – crabeater seal	Marine	Least Concern Unknown
	Ommatophoca rossii – Ross seal	Marine	Least Concern Unknown
Otariidae (eared seals)	*Arctocephalus gazella* – Antarctic fur seal	Marine	Least Concern Decreasing
	Arctocephalus tropicalis – subantarctic fur seal	Vulnerable	Least Concern Stable

EPBC Act = *Environment Protection and Biodiversity Conservation Act 1999*; IUCN = International Union for Conservation of Nature

Source: IUCN (2021)

Leopard, crabeater and Ross seals have a circumpolar distribution. Crabeater seals are relatively abundant, whereas leopard and Ross seals disperse widely, distribute sparsely and are very difficult to study. Leopard seals typically occupy the Antarctic pack ice zone where they breed. However, these seals also travel to areas north of the Antarctic Polar Frontal Zone, including to subantarctic islands, South America, South Africa and Australia (Staniland et al. 2018). Similarly, Ross seals sometimes travel to subantarctic islands but, like leopard seals, depend on the sea ice as a breeding platform (Arcalís-Planas et al. 2015). Post-moult, Ross seals migrate north (Wege et al. 2021).

The last time circumpolar population estimates were obtained for these species was in the late 1990s during the Antarctic Pack Ice Seal (APIS) survey (Southwell et al. 2012). Estimates of the global population of crabeater seals have ranged from 2 to 5 million individuals in the mid-1950s (Scheffer 1958) to about 75 million in the early 1970s (Erickson et al. 1971) and 11–12 million in 1990 (Erickson & Hanson 1990). In 1999–2000, the APIS survey, a detailed aerial survey, covered an area of 1.5 million km^2 from 64°E to 150°E. The survey estimated fewer than 1 million individuals in the survey area, with a range of 0.7–1.4 million. Thus, crabeater seals appear to be abundant, but earlier estimates were probably too high. Analysis of satellite imagery shows that leopard and Ross seals also appear to be abundant, with numbers in the tens of thousands, but fewer than crabeater seals (Southwell et al. 2012). Ross seals are the rarest of the pack ice seals, comprising only about 1% of Antarctic seals. They differ from the other seals in that they breed and moult in the pack ice but forage in the open ocean most of the year (Wege et al. 2021).

How the pack ice seals respond to environmental stressors may vary among species (Ainley et al. 2015). Changes in the structure and size of ice floes could lead to the loss of their breeding habitat. Furthermore, a reduction in sea ice persistence may reduce the availability of Antarctic krill, an important food source for all pack ice seals, especially crabeater seals, whose diet can comprise 90% Antarctic krill (Hückstädt et al. 2012). In the western region of the Antarctic Peninsula, major changes in wind strength, sea ice extent and duration, and the characteristics of the ACC are expected to alter the distribution of krill and therefore the distribution of crabeater seals. As the Southern Ocean continues to warm, krill stocks will decrease in the areas they currently occupy. Optimal conditions for krill are predicted to shift south, and whether krill predators such as crabeater seals will be able to adapt or not will determine their future (Hückstädt et al. 2020). Leopard seals have the most diverse diet among the ice seals and may be the least likely to be affected immediately by changes in food availability. However, depending on the rate, kind and magnitude of environmental changes, these changes will affect them eventually.

Weddell seals (*Leptonychotes weddellii*) occur in the pack ice but breed on the nearshore fast ice that surrounds the Antarctic continent. Their biology is comparatively well studied. There may be around 730,000 individuals, which remain in the Antarctic region throughout the year. Weddell seals have a high level of fidelity to their breeding sites, and have been observed to travel more than 300 km in winter (Heerah et al. 2016). They dive on average to 125 m but can dive to more than 700 m (Goetz et al. 2017). Their breeding season generally commences in October–November; females give birth to pups on the sea ice near breathing holes and nurse them for 5–6 weeks. Warming temperatures may reduce the energetic cost for seals but also reduce access to suitable breeding habitat and sufficient food resources (Guo 2020).

Southern elephant seals (*Mirounga leonina*) have a circumpolar distribution; they breed on subantarctic islands, including Macquarie Island – this is the only breeding population in the Pacific sector of the Southern Ocean (Volzke et al. 2021). Their major foraging habitats are the Antarctic continental shelf and the Kerguelen Plateau in the southern Indian Ocean (Hindell et al. 2016). The species is highly dimorphic – males are significantly larger than females – and exhibits gender-related difference in foraging strategies and diet. For example, females tend to forage in the open ocean and mainly consume small fish, whereas males are more likely to forage on the continental shelf where they hunt fish, squid and krill (Labrousse et al. 2017).

Southern elephant seals, particularly young males, have numerous haul-out sites on the Antarctic continent, where they spend most of the summer moulting. On Macquarie Island, about 155,000 southern elephant seals may have been present in the 1950s; however, there has been a long-term decline in the population since, which appears to be continuing. The reasons for this are difficult to investigate as this species migrates over long distances for 8–10 months per year (Learmonth et al. 2006). However, elephant seals probably experience different pressures throughout the year, as well as at various stages of their lifecycle. For example, there appears to be a link between sea ice extent in the summer foraging areas of females and the survival of their offspring. Extensive sea ice may exclude the seals from high-quality foraging areas, which in turn affects the survival of their pups (van den Hoff et al. 2014). The decline of the southern elephant seal population has recently been linked to poor foraging success because changing oceanic conditions have reduced prey availability (Clausius et al. 2017). Occasionally, elephant seals are entangled and drowned in longline gear set for toothfish. Low levels of mortality are very unlikely to lead to significant population impacts (Clausius et al. 2017, van den Hoff et al. 2017).

The complexity in the ecology of this wide-ranging species, which occupies different habitats, makes it challenging to predict how climate change will affect the population. Changes in habitat quality will depend on the region; hence, responses of populations and individuals will vary (Hindell et al. 2016).

Eared seals (Otariidae)

Fur seals (*Arctocephalus* spp.) inhabit the subantarctic islands and occur as far south as the Antarctic continent, where they are infrequent visitors. Several fur seal populations still appear to be increasing, albeit at varying rates depending on location. On Macquarie Island, the very small breeding populations of Antarctic (*Arctocephalus gazella*), subantarctic (*A. tropicalis*) and New Zealand (*A. forsteri*) fur seals appear to be stable.

Whales (Cetacea)

The Southern Ocean is the prime feeding ground for baleen whales (Mysticeti). Nine species and subspecies of these large whales occur in the Southern Ocean: the Antarctic blue (*Balaenoptera musculus intermedia*), pygmy blue (*B. musculus brevicauda*), fin (*B. physalus*), humpback (*Megaptera novaeangliae*), dwarf minke (*B. acutorostrata*), sei (*B. borealis*), minke (*B. bonaerensis*), southern right (*Eubalaena australis*) and pygmy right (*Caperea marginata*). Some species, such as blue and fin whales, hunt throughout the summer in the Southern Ocean, and migrate north in winter to mate and calve in low-latitude waters (Shabangu et al. 2020). Key baleen whale species are assessed under the EPBC Act and by the IUCN (Table 4). At least 22 species of toothed whales (Odontoceti) also occur regularly in the Southern Ocean (Van Waerebeek et al. 2010). The 2 most commonly sighted toothed whale species are killer whales

(*Orcinus orca*) and sperm whales (*Physeter macrocephalus*).

In the Southern Hemisphere, baleen whales travel long distances from their feeding areas in the Southern Ocean to their nursery areas at lower latitudes. For 80–90% of the world's whales, the Southern Ocean Whale Sanctuary, established in 1994, is the major feeding ground in the summer (IWC 1995). As major krill consumers, baleen whales depend on lower levels of the food web (i.e. their survival is linked closely to levels of primary productivity) (Leaper et al. 2006). Whales play an important role in biogeophysical cycling of iron. Whale defecation deposits large quantities of iron into the marine environment and promotes ocean productivity – for example, in the otherwise iron-poor waters of the Southern Ocean. This biological fertilisation is likely to increase krill abundance and even fishery yields (Lavery et al. 2014).

Knowledge about the size and structure of whale populations is very limited. Estimating the abundance of whale populations is a complex and complicated process. Issues can arise with species identifications, the timing of surveys, the areas covered and even the response of species to the presence of vessels (Leaper et al. 2008). Many species have a circumpolar distribution, but their species-specific behaviours differ significantly. For example, although sperm whales use the Southern Ocean during summer, generally only the large males visit the regions south of the Antarctic Polar Frontal Zone (Leaper et al. 2008).

Table 4 National (EPBC Act) and international (IUCN) status of baleen whales (Mysticeti) in Australia's jurisdiction

Species	EPBC Act	IUCN – global population trend
Balaenoptera acutorostrata – dwarf minke whale (subspecies)	(Listed at species level)	(Listed at species level)
Balaenoptera bonaerensis – Antarctic minke whale	Migratory	Least Concern Unknown
Balaenoptera borealis – sei whale	Vulnerable	Endangered Increasing
Balaenoptera musculus brevicauda – pygmy blue whale (subspecies)	(Listed at species level)	(Listed at species level)
Balaenoptera musculus intermedia – Antarctic blue whale	Endangered	Critically Endangered Increasing
Balaenoptera physalus – fin whale	Vulnerable	Vulnerable Increasing

EPBC Act = *Environment Protection and Biodiversity Conservation Act 1999*; IUCN = International Union for Conservation of Nature
Source: IUCN (2021)

Although various whale populations have shown signs of a slow recovery following the prohibition of whaling, and certain protections are now in place, in the face of a warming climate, baleen whales may be particularly at risk (Constable et al. 2014). Models predict a marked slowdown in the further recovery of whale populations (Tulloch et al. 2018). Whales require stable environments; their life histories are linked tightly to water temperatures and food availability, making whales particularly sensitive to climate change (Tulloch et al. 2018). Species feeding in the mid-latitudes (40–60°S), the regions around the ACC, are likely to be particularly affected by climate change. There are strong interactions between temperature, krill density, body condition and breeding success; for example, food availability during the early weeks of gestation affects breeding success of southern right whales (Seyboth et al. 2016).

Baleen whales (Mysticeti)

The largest creatures on Earth, Antarctic blue whales can reach lengths of up to 27 m. They and various subspecies were commercially hunted from 1904 to 1972. The remaining population is only 3% of the pre-exploitation population. We still understand little about their biology, and attempts to estimate their population size have large uncertainties associated with them. Hunting ceased only in 1972, although it was prohibited in the Southern Ocean in 1965–66. Currently, the greatest threats these whales face are declining food sources associated with ocean warming and increasing ocean acidification (Cooke 2018).

The most comprehensively studied whale is the humpback whale; its distribution and stock abundance are probably the best known of any whale species. The International Whaling Commission distinguishes 7 separate breeding stocks of humpback whales in the Southern Hemisphere, and an eighth that occupies the northern Indian Ocean but does not migrate to Antarctic waters (Branch 2011). The various breeding stocks of humpback whales vary in size (Branch 2006). The largest stock is probably breeding stock D, which migrates annually from summer feeding grounds in Antarctica to northern Western Australia for winter (Kent et al. 2012). This stock has a long history of exploitation (Chittleborough 1965). However, since whaling operations ceased, humpback whales have made a remarkable recovery. Recent surveys indicate that the stock is increasing to a point that its delisting as a threatened species under Australian legislation was proposed in 2016 (Bejder et al. 2016); the possibility of delisting humpback whales from Australia’s EPBC Act is currently being reviewed (DAWE 2021b).

Since 1966, humpback whales have been protected legally from commercial whaling. However, they can still be killed under Article VIII of the International Convention for the Regulation of Whaling – including in Antarctica – provided that the government of a member nation has issued a permit (IWC 2021).

Toothed whales (Odontoceti)

Killer whales are the largest species of the dolphin family. Once regarded as a single worldwide species, they were divided into various ecotypes because of marked differences in their morphology, ecology and vocalisation. In Antarctica, 3 types are recognised based on appearance and diet (Pitman & Ensor 2003). The high level of diversity in a species makes its taxonomy challenging but, based on the known variability and genetic evidence, (Morin et al. 2010) suggested elevating these types to species.

Killer and sperm whales depredate toothfish from longlines, including in Australia’s fleet that fishes at Heard Island and McDonald

Islands (van den Hoff et al. 2017, Tixier et al. 2020). Because of the intelligence of these species, population increases and the desirability of toothfish as a rich source of calories, mitigation of this activity has proven very difficult (Richard et al. 2020).

Sperm whales rank among the least understood whale species. Commercial activities severely reduced their population, particularly from 1945 to 1975. The most recent assessment concluded that, globally, sperm whales are currently at 32% of their pre-whaling population levels (Whitehead 2002). A survey off Western Australia also documented that this species shows no sign of recovery (Carroll et al. 2014).

Fish

The Southern Ocean covers about 35 million km^2, or 10% of Earth's oceans. In some regions, the ocean is more than 5,000 m deep; shallower waters occur in coastal regions and at submarine ridges. Of the roughly 20,000 different marine fish species, only 322 (1.6%) used to be known from the Southern Ocean, but the level of endemism (i.e. species are found nowhere else) is about 3 times higher than in other isolated marine areas (Eastman 2005). New species are still being identified. For example, the *Biogeographic atlas of the Southern Ocean* (Duhamel et al. 2014) lists 374 species. Fish occupy a range of habitats in the water column that extends from the surface to the ocean floor. Most species (about 63%) live on the ocean floor (benthic), and about 26% inhabit the water column at 200–1,000 m depth (mesopelagic) (Eastman 1993).

Antarctic fish evolved in an environment that remained stable for millions of years (Navarro et al. 2019). Antarctic fish are highly stenothermal – that is, they can survive in only a narrow temperature range. Temperatures in the Southern Ocean are close to the freezing point of salt water (–1.9 °C) and vary annually by less than 1 °C (Hunt et al. 2003).

Relatively little is known about the capacity of Antarctic fish to adapt physiologically to climate change impacts, such as increasing ocean temperatures and acidification. Icefishes have no haemoglobin to carry oxygen in their bloodstream and, hence, rely on dissolved oxygen levels. Thus, they may be affected as oxygen saturation levels decline with rising temperatures (Constable et al. 2014). Experimental research has shown that heat stress can cause changes in metabolic processes and enzyme activity. The effects depend on the level of temperature change, the duration of the exposure and the species (Forgati et al. 2017). For example, rock cods (*Notothenia* spp.) experience oxidative damage to their lipid tissues and antioxidant systems after long-term exposure to increased temperatures (Klein et al. 2017).

Cod icefish (notothenioids) make up about one-third of the known 374 fish species in the Southern Ocean (Duhamel et al. 2014), and many species of this group are endemic to the region (Cheng et al. 2003). Since Antarctic fish species evolved over millions of years in subzero temperatures, they have many physiological and biochemical traits (e.g. antifreeze in their blood) that enable them to thrive in their chronically frigid environment (Beers & Jayasundara 2015).

Among the fish species that are important prey for higher Antarctic predators, such as penguins and Antarctic toothfish (*Dissostichus mawsoni*), is the Antarctic silverfish (*Pleuragramma antarctica*). The Antarctic silverfish has a circumpolar distribution and is a mesopelagic notothenioid that feeds mainly on Antarctic and crystal krill (*Euphausia crystallorophias*). The silverfish occurs throughout the Southern Ocean, and is a key species and major forage fish in the pelagic ecosystem on the Antarctic continental shelf (Mintenbeck & Torres 2017).

Like all notothenioid species, Antarctic silverfish lack a swim bladder. Many notothenioids live on the ocean floor and, thus, do not need a swim bladder, whereas silverfish live in the water column, and have achieved near-neutral buoyancy through an increase in fat deposits, and a reduction in skeletal mass and body density (Wöhrmann 1998, Voskoboinikova et al. 2017). Like many fish in the Southern Ocean, Antarctic silverfish are long-lived, mature late, grow slowly and have a relatively low fecundity (Mintenbeck et al. 2012). They spawn underneath the coastal sea ice, probably in late winter. Because sea ice is important for its reproduction, this species is vulnerable to the effects of climate change. Furthermore, Antarctic silverfish are adapted to stable conditions and a water temperature of −2 °C. In the waters off the western Antarctic Peninsula, a rapidly warming region, the stocks of the silverfish appear to have collapsed. Polar species such as the Antarctic silverfish may be affected once the conditions in their current area of distribution are no longer favourable. As the ocean grows warmer, a recovery of the stock is unlikely, and an important prey of many species may be lost (Mintenbeck & Torres 2017).

Another important element of the fish fauna is the Antarctic toothfish, a large notothenioid, with a circumpolar distribution that extends north to the Antarctic Convergence and into subantarctic waters (Hanchet et al. 2015). This species is commercially exploited (see Commercial fishing). Adults measure around 160 cm in length; the longest Antarctic toothfish caught measured 210 cm and weighed 120 kg. Although they lack a swim bladder, adult toothfish appear to forage through the entire water column and may acquire near-neutral buoyancy through the accumulation of dietary lipids. Buoyancy changes with level of maturation, diet and migration (Hanchet et al. 2015).

It appears that Antarctic toothfish, which have antifreeze glycoproteins in their bloodstream, occur continuously along the continental slope and shelf of the Antarctic continent and reach areas up to 57°S. In comparison, the Patagonian toothfish (*D. eleginoides*) mainly occupies the insular and continental shelves in the subantarctic and does not have antifreeze glycoproteins. In the waters off the South Sandwich Islands, on the BANZARE Bank and around Bouvet Island, the Antarctic and Patagonian toothfish species overlap; occasional vagrants of both species are observed far to the north of their typical distributions (Hanchet et al. 2010, Péron et al. 2016, Yates et al. 2019).

Antarctic toothfish are generalist predators, and large adults are at the highest trophic level (i.e. highest in the food chain) of fish off East Antarctica (Park et al. 2015). Antarctic toothfish compete with Weddell seals for prey, but the seals also consume toothfish (Ainley et al. 2021), as do sperm and killer whales, and colossal squid (*Mesonychoteuthis hamiltoni*) (Hanchet et al. 2015). The energy density of Antarctic toothfish is twice as high as that of the seals' common prey, Antarctic silverfish and dusky rockcod (*Trematomus newnesi*) (Goetz et al. 2017), and the body mass of large toothfish (around 120 kg) is up to 3 orders of magnitude higher than that of silverfish. Weddell seals may consume large toothfish that are half the seals' length (Ainley et al. 2021).

Another fish species of importance to predators such as king penguins and some commercial fishers is mackerel icefish (*Champsocephalus gunnari*). This small, pelagic, schooling fish occurs mainly at depths of 20–250 m and performs a diurnal migration. In late winter, it is an important prey item for king penguins; as much as 17% of the chicks' diet can be mackerel icefish. This oily fish provides sustenance to the chicks at the end of a long winter, during which they receive food only intermittently. Unlike many other Antarctic fish, mackerel icefish reach maturity relatively early (age 3–4 years). The fish spawn in coastal areas in late winter; females produce 10,000–20,000 eggs that hatch after having spent about 3 months near the seabed (AFMA 2015).

Assessment Marine vertebrates

2021

Limited confidence

The condition of Antarctic marine species varies between species. Populations of fish, whales and penguins are in a good condition, but elephant seal and seabird numbers are poor and deteriorating. The trend for many species is unclear because of insufficient data.

Assessment Albatrosses

2021 **2016** **2011**

Adequate confidence

All but one albatross species are endangered. Seabird deaths in Australian fisheries and in the Conservation of Antarctic Marine Living Resources area are greatly reduced, but seabirds continue to interact at unsustainable levels with fisheries outside Australia's jurisdiction.

Assessment Other flying seabirds

Limited confidence

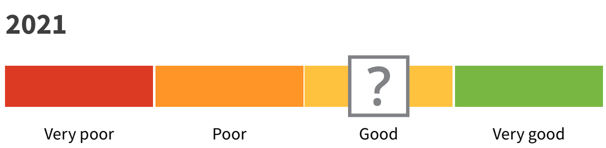
Status and trends vary with species and location. Population data, if available, cover only limited areas. At Macquarie Island, several petrel species have returned to the island since eradication of non-native predators.

Assessment Penguins

Somewhat adequate confidence

Penguins are relatively well studied. Many populations appear to be stable or increasing, but, at Macquarie Island, gentoo penguins appear to be decreasing.

Assessment True seals



Limited confidence

Because of their distribution and behaviours, it is difficult to assess populations of true seals in Antarctica. The last comprehensive seal survey occurred in 1999–2000.

Assessment Eared seals

Adequate confidence

Status and trends vary with species and location. At Macquarie Island, the small populations of fur seals appear to be stable, but elephant seals are still in decline.

Assessment Baleen whales

Limited confidence

Some species have recovered well since whaling ceased in the Southern Ocean, whereas for others there are no signs of recovery. For many species, population data are difficult to acquire.

Assessment Toothed whales

Limited confidence

Killer whales are the best studied toothed whales. However, uncertainties about their taxonomy make population assessments difficult.

Assessment Patagonian toothfish

2021

Adequate confidence

Regular pre-recruit surveys, tagging studies and biennial stock assessments provide relatively high levels of information on current status and trends of fished stocks in Australia's jurisdiction. Current stock levels are above (Macquarie Island) or just below (Heard Island and McDonald Islands) the long-term target level prescribed in the harvest strategy.

Assessment Antarctic toothfish

2021

Limited confidence

Data for this species are limited. Declines in illegal, unreported and unregulated fishing, and recent research in an exploratory fishery indicate that stocks off the Australian Antarctic Territory are healthy.

Assessment Mackerel icefish

2021

Adequate confidence

Annual surveys and stock assessments provide relatively high levels of information on current status and trends of this species at Heard Island and McDonald Islands. Current fishing levels are sustainable.

Marine invertebrates

The Southern Ocean is home to more than 5,000 invertebrate species. Antarctic invertebrate communities form a significant part of the marine food web because they form habitat, and cycle and sequester carbon and other nutrients. Marine organisms sequester inorganic carbon by converting it into organic carbon and storing it in their bodies (blue carbon). There are strong interactions between blue carbon and loss of sea ice, leading to a negative (mitigating) feedback on climate change effects. The growth season of phytoplankton occurs in summer when less sea ice covers the Southern Ocean (including through the retreat of ice shelves), allowing more light to penetrate the ocean waters than in winter. Through increased primary production by phytoplankton, more carbon reaches the seabed. Benthic communities consume plankton that has died and sunk to the bottom of the ocean. As benthic communities grow, age and die, the carbon is sequestered into the sediments and stored (Barnes et al. 2018). This occurs mostly in deeper shelf waters, but also in some shallow areas. Thus, climate change can lead to a greater carbon drawdown in Antarctica through this benthic–pelagic coupling and the growth of the benthic communities.

Where glaciers retreat and ice shelves disintegrate, new habitat opens that is likely to be colonised by algal and invertebrate communities, increasing the drawdown and storage mechanism. However, as Antarctica warms, more glaciers and ice shelves calve off icebergs. Icebergs can scour the substrate (strike the seabed) in coastal shallows, or further offshore, destroying benthic communities and making the organisms available for scavengers in the lower water column (Dunlop et al. 2014). Consequently, carbon sequestration is reduced. Scouring may be constrained to areas where there are many icebergs, and where winds drive them into shallow waters (i.e. much of the Antarctic Peninsula). Giant icebergs can persist for many years; for example, iceberg A23A (1,760 km2) calved off the Filchner Ice Shelf, Weddell Sea, in 1986 and moved only about 200 km in 30 years. Scouring by giant icebergs can destroy nearly all benthic organisms; it may take decades to hundreds of years for these communities to recover, provided no further major disturbances occur (Barnes 2017). Although scouring is detrimental to benthic organisms, it also mobilises carbon, effectively fertilising affected areas and increasing primary production, particularly in areas where productivity was low (Barnes et al. 2018). At the western Antarctic Peninsula, a region where some of the most significant environmental changes are occurring, scouring may mobilise about 80,000 t of carbon per year to the marine environment. However, carbon storage is disrupted where benthic communities do not have the opportunity to recover – for example, as a result of ongoing iceberg calving and continued scouring (Barnes 2017).

Benthic and pelagic marine invertebrates will be affected by warming ocean temperatures, acidification, sediment input from melting glaciers and changes in nutrient cycling associated with climate change; they will also be affected by commercial fishing activities and invasive species (Brasier et al. 2021).

Benthic invertebrates

The bottom of the Southern Ocean offers rich habitats for many species, which grow much more slowly than their temperate equivalents. Invertebrate taxa living on the continental shelf (0–1,000 m deep) and in the deep ocean (more than 1,000 m deep) encompass 7,210 known species (De Broyer & Danis 2011). At depth, environmental conditions are stable, and species communities and assemblages do not appear to change much. Sea spiders, sea urchins, marine worms, molluscs, sponges and other creatures are highly diverse, with a substantial percentage of endemic species (Brandt et al. 2006, Rapp et al. 2011). The benthic invertebrate communities of Antarctica, especially those living outside the intertidal zone – for example, in the high Antarctic – exist in a very stable environment where temperatures fluctuate as little as 1.5 °C throughout the year (Peck 2005). These stenothermal environments (i.e. with a narrow temperature range) came into existence about 4–5 million years ago as the waters surrounding Antarctica cooled (Pörtner et al. 2007).

It is difficult to predict how warming of the ocean may affect organisms that have adapted to live in a very narrow temperature range. Many invertebrates die or cannot perform crucial biological activities when temperatures are raised 5–10 °C (Pörtner et al. 2007). However, these results are based on experiments during which temperatures are increased rather quickly compared with rates of change expected in nature. The more gradually environmental change occurs, the better are the chances for at least some species to adapt to the changing conditions.

Ocean acidification will have different effects on the various species of invertebrates (Dupont et al. 2010, Hancock et al. 2020). 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 and increased mortality (Hendriks et al. 2010, Hancock et al. 2020, Brasier et al. 2021).

For example, fertilisation of the Antarctic nemertean (ribbon) worm (*Parborlasia corrugatus*) may not be affected by higher acidity, and experimental work showed that egg development appeared resilient when seawater pH was reduced to neutral. However, abnormalities occurred at a later (blastula) stage of the embryos' development (Ericson et al. 2010). Although the pH changes that produced the abnormalities are not predicted to occur soon (i.e. by 2100), they are expected if the oceans continue to acidify in the long term (i.e. beyond 2100) (Ericson et al. 2010). Other factors, such as temperature and nutrient availability, also play a part.

Plankton

The deep, turbulent, cold Southern Ocean separates Antarctica from the other continents. Although upwelling currents around the continent deliver nutrients from the deep to the surface waters, plankton (pelagic organisms) plays a vital role in the biological pump, a mechanism through which atmospheric carbon is sequestered and eventually delivered to the ocean floor. Extraordinarily huge masses of phytoplankton (photosynthetic microbes) convert about 90 gigatonnes of dissolved carbon dioxide per year into organic carbon (Cavan et al. 2019).

Krill is among the largest and most ecologically important species of pelagic invertebrates (zooplankton). Near the surface of the ocean, grazers such as Antarctic krill consume phytoplankton and other microorganisms, and are themselves eaten by higher-order predators. These abundant food resources sustain large numbers of predators, including whales, seals, seabirds, fish and squid.

Krill species also play an important role in the nutrient cycling of the Southern Ocean, simply because of their extraordinary abundance. Although the total biomass of Antarctic krill is not easy to estimate, combining acoustic and trawl data provides estimates of krill biomass of about 215 million tonnes (Atkinson et al. 2009). The movement and action of this mass – including daily vertical migration, fast swim speed, rapidly sinking faecal pellets and huge grazing capacity – make krill a critical influence in the stimulation of primary productivity and movement of nutrients through the water column.

Krill populations are already under pressure through increasing ocean temperatures and changes in sea ice cover. Juvenile (larval) krill continues to feed during winter to survive and recruit to the stock during the following spring. The main food source comprises algae that grow on the underside of the sea ice. The dependence of juvenile krill on sea ice algae makes new cohorts particularly vulnerable to reductions in sea ice extent and duration (Bernard et al. 2019). During summer, krill still consume sea ice algae but also use other carbon sources such as pelagic diatoms. This is particularly true for the crystal krill, an omnivorous krill species. Thus, although krill may be more adaptable to changing summer conditions, in winter their reliance on food resources linked to sea ice is a major limitation to their survival (Kohlbach et al. 2019). The combined effects of these pressures and an increase in ocean acidification could significantly compromise krill recruitment within a century (Kawaguchi et al. 2013).

With regard to commercial krill fishing operations off East Antarctica, broadscale surveys of Antarctic krill are conducted at roughly 10-year intervals, and enable the assessment of status. However, the assessment of trends is challenging. Although catches are currently well below sustainable levels, future impacts of climate change will need to be considered.

Human environment

Humans maintain a presence in Antarctica and have a direct influence on some areas, particularly ice-free areas, through various activities. Continent-wide, there are about 1,100 people in winter and 4,400 people in summer on the various research stations (World Population Review 2021).

Before the COVID-19 pandemic, more ships and aircraft were visiting Antarctica than ever before, making pollution with hydrocarbons (fuel, oil) through leakage and spills a real risk to the environment, particularly for benthic communities (Polmear et al. 2015). Disturbance to wildlife can be an issue; this includes visits to breeding areas, and noise pollution by aircraft, ships and machinery. Even simple activities such as walking can affect habitat, particularly soils. Trampling of soils can result in their compaction, which alters the surface structure, nutrient cycles, and soil and plant communities (Tejedo et al. 2014).

Antarctic stations

In 2017, 29 nations collectively occupied 40 Antarctic year-round stations, and another 36 facilities operated only during summer (October to March) (COMNAP 2017). Some 27 stations had been constructed before the adoption of the Environmental Protocol to the Antarctic Treaty (Brooks et al. 2019). Several old, abandoned stations continue to deteriorate. In addition, field huts and refuges, weather stations, runways, historical huts and tourist camps increase the human footprint in Antarctica (Brooks et al. 2019). On the continent, construction of stations is continuing; for example, in 2018, China constructed a temporary station at Inexpressible Island, Ross Sea, while finalising a Comprehensive Environmental Evaluation for the construction of a permanent base there.

Sixty stations have been built on gravel or soil sites and 17 on rock. Gravel or soil sites occupy areas that are often breeding habitat of wildlife or where terrestrial vegetation is abundant. Permanent alteration of the substratum can lead to changes in the geomorphology and water cycle, and loss of wilderness and aesthetic values (Brooks et al. 2019).

Australian Antarctic stations

Australia maintains 3 year-round continental research stations (Casey, Davis and Mawson), and 1 at subantarctic Macquarie Island. Remote field bases operate during the summer season, including Wilkins Aerodrome, 70 km inland from Casey Station. The station populations range from 40 to 100 expeditioners over summer, and 15 to 20 over winter. Each season, about 500 expeditioners travel south with the Australian Antarctic Program.

The Australian Antarctic Division (AAD) maintains an Environmental Management System (EMS) consistent with AS/NZS ISO 14001. The EMS is a systematic means of managing the AAD's activities, using a set of operational indicators to monitor and assess human impact on the environment associated with the Australian Antarctic Program during the planning, operational and continual improvement stages.

The operation of Antarctic stations requires a significant amount of energy. The total fuel consumption of Antarctic operations was relatively steady over 2015–16 to 2019–20, and ranged from 6.4 to 7.1 megalitres (ML). Shipping and aircraft operations use 40–45% and 21–24% of the total fuel, respectively (see Shipping and air operations). The remainder is used in station operations, mainly to generate electricity (Table 5).

Electricity is needed to heat buildings and water tanks, to provide light, especially through the long Antarctic winter, to operate workshops, and so on. From 2015–16 to 2019–20, overall electricity use per person increased by 11.4%, from 0.166 terajoules (TJ) to 0.185 TJ (46,100 kilowatt hours (kWh) to 51,390 kWh).

Table 5 Summary of environmental performance of Antarctic station operations by season

Variable	2015–16	2016–17	2017–18	2018–19	2019–20
Total waste (t)	304	177	263	252	201
Waste to landfill (t)	169	147	164	191	90
Waste recycled (t)	135	30	78	61	111
Liquid waste treated and disposed of (t)	17	43	10	22	54
Water use (ML)	6.27	6.79	6.68	6.83	6.15
Electricity generated by diesel (TJ)	18.5	19.7	20.6	21.0	21.5
Electricity generated by renewables (TJ)	5.4	5.9	4.0	2.4	1.7
Operational diesel fuel (ML)	2.27	2.09	2.25	2.39	2.46

ML = megalitre; t = tonne; TJ = terajoule
a Comprises diesel used for electricity generation, vehicles, plant, incinerators and boilers.
Sources: DAWE (2020a); DAWE (2020b) for 2019–20 operational diesel fuel data

The total electricity generated by diesel increased by 6.5% from 18.5 TJ in 2015–16 to 21.5 TJ in 2019–20. At Mawson Station, the wind turbine has suffered some technical issues in recent years. In 2019–20, it produced only 1.7 TJ (420,200 kWh), compared with 5.9 TJ (1.64×10^6 kWh) in 2016–17, a decrease of 68% (DAWE 2020a).

Water

Free-flowing water for human use is greatly limited in Antarctica. On stations, water is required for domestic uses (kitchen, showers, laundries), in workshops and in other operational buildings. Water is stored in large tanks. Special tanks designated for firefighting in case of an emergency comprise two-thirds of the water stores on stations. These tanks are heated so that the water can be used all the time. Water is produced by melting snow and ice in special facilities, or, at times during summer, from seawater using reverse osmosis.

Water-saving behaviours are encouraged among expeditioners. However, the consumption of water (and energy) does not always reflect the size of the station population but may reflect an increase in, or change of, activities. For example, overall water consumption increased during 2018–19 compared with previous years, as did energy consumption, although there were fewer expeditioners than in previous years (DEE 2019).

Overall, water consumption increased from 6.27 ML in 2015–16 to 6.83 ML in 2018–19. As a result of the COVID-19 pandemic in 2019–20 and reduced operational activities, water consumption dropped slightly to 6.15 ML (Table 5).

Waste management

Each year, waste and materials no longer required on station are returned to Australia for recycling, re-use or disposal. Waste typically includes general landfill and commingled recycling, such as paper, glass, aluminium and plastic (polyethylene terephthalate – PET, and high-density polyethylene – HDPE), sewage sludge, paint, oil, steel, copper, brass, building materials and laboratory chemicals.

Quantities of waste returned to Australia vary annually and with capacity of ships to transport these materials. From 2015–16 to 2019–20, the amounts of liquid taken from Antarctica ranged from 10 to 54 t. Over the same period, the quantities of materials sent to landfill ranged from 90 to 191 t, but 73% more recyclable material was returned to Australia (DAWE 2020b, DAWE 2020a).

Wastewater derives from various parts of a station, and includes greywater from the kitchen, showers, workshops and laboratories. This water contains a mix of contaminants, including chemicals, detergents, medications and cosmetics. Generally, wastewater treatments are used to reduce the level of nutrients and microorganisms (Corbett et al. 2014). The treated water is released into the nearshore environment, and solids are returned to Australia.

Shipping and air operations

Each year, various ships and aircraft transport people and goods to and from Australia's 4 permanently occupied research stations of Casey, Davis, Mawson and Macquarie Island. During recent years, the winter populations at the Australian stations have remained relatively stable; there have typically been 16–22 people on each of the continental stations, and 13–15 on Macquarie Island. For many years, Davis Station had the largest summer population, with up to 100 personnel. However, with efforts to modernise station facilities, this number is likely to increase over the coming years. Casey Station has a much larger number of expeditioners coming and going throughout the summer season because of the improved access to Antarctica by air transport. Prevailing weather conditions do not allow use of the runway during winter.

The AAD undertakes voyages for a range of purposes, primarily resupply of the stations, and deployment and retrieval of personnel, as well as marine science research. The new icebreaker RSV *Nuyina* (see case study: Cultural connections of RSV Nuyina) arrived in Hobart in October 2021, and will be the primary vessel used for logistics and research conducted under the Australian Antarctic Program. Occasionally, the AAD charters other vessels to augment activities, such as waste removal, Southern Ocean and marine science research activities, and transport of personnel to and from Macquarie Island.

The AAD also uses a variety of aircraft to transport passengers and cargo, including the Royal Australian Air Force's C-17 Globemaster III, which has delivered heavy cargo to Wilkins Aerodrome in support of the Australian Antarctic Program. Use of this type of heavy-lift aircraft has improved the AAD's logistical and scientific capabilities.

Fuel consumption by vessels decreased by 34.7% from 3.34 ML in 2015–16 to 2.48 ML in 2019–20; fuel use by aircraft remained relatively steady, averaging 1.49 ML in this period (DAWE 2020a).

Over the past 5 years, total greenhouse gas emissions (tonnes of CO_2 equivalent) decreased by 10% from 19,894 t in 2015–16 to 17,917 t in 2019–20 (Table 6), partly due to variations in operational demands. Variations in the use of fuel for ships is related to the size and number of vessels used and whether or not marine science voyages are undertaken. For example, in 2017–18, the RSV *Aurora Australis* undertook 4 voyages, and no additional vessel was chartered as in the previous 2 seasons (Australian Antarctic Program 2021). Sea ice conditions also influence fuel use; when the sea ice extent is reduced, less fuel is required to break ice.

Table 6 Summary of environmental performance of Antarctic shipping and air operations by season

Variable	2015–16	2016–17	2017–18	2018–19	2019–20
Aircraft fuel (ML)	1.49	1.56	1.57	1.55	1.31
Ship fuel (ML)	3.34	3.13	2.57	2.85	2.48
Total fuel (kL)	7.10	6.78	6.39	6.72	6.25
Total greenhouse gas emissions (t CO_2 equivalent)	19,894	19,002	17,829	18,996	17,917

CO_2 = carbon dioxide; kL = kilolitre; ML = megalitre; t = tonne
Sources: DAWE (2020a); 2019–20: DAWE (2020b)

Case study Cultural connections of RSV *Nuyina*

tunapri Palawa milangkani milaythina paywuta. tunapri muylatina muka-ti, nipakawa nuritinga kani pakana milaythina & muka liyanana Antarctica.

muka tina, pinungana & muta tapilti Antarctica-tu paywuta.

Nuyina, lukrapina lakarana, tapilti makuminya maytawinya-ta & yula; nara kipli muka-ti mapiya Antarctica.

liyanana panitha; muka ningina latu. warr! waranta pumili manina ngayapi, narakupa milaythina-nara-mapali & tina muka kitina, maytawinya lakarana.

manta manta.

(Tasmanian Aboriginal knowledge comes from Country, and is connected to country since the beginning of time.

This knowledge embraces sea Country, and the waters which carry our stories that connect us with the icy land and seas of Antarctica.

Marine animals, fish and birds migrate from northern lands to Antarctica and back, every year as they have done since creation.

The big ice-breaker Nuyina *follows the path of the muttonbird and whale that feed in the waters around Antarctica.*

But the ice is melting; ocean temperatures are rising! We must bring our planet back to life, care for our Country and the ocean's lifeworlds – from the smallest krill to the largest whale, for all the times to come.)

In palawa kani, the language of Tasmanian Aboriginal peoples, with thanks to the Tasmanian Aboriginal Centre.

Australia's new Antarctic icebreaker, RSV *Nuyina* (Figure 14), which arrived in Hobart in October 2021, will be the main lifeline to Australia's Antarctic and subantarctic research stations. It will be the central platform of the nation's Antarctic and Southern Ocean scientific research, and provide expanded and improved capabilities to manage Australia's environmental footprint in the region.

'nuyina' – pronounced noy-yee-nah – means 'southern lights' in palawa kani, the language of Tasmanian Indigenous people.

The southern lights, also known as the aurora australis, are a phenomenon in the high altitudes of the atmosphere over Antarctica that reaches northwards to light up Australian – and particularly Tasmanian – skies. The first Australian Antarctic ship, Sir Douglas Mawson's SY *Aurora*, was named after the same phenomenon, as was Australia's first icebreaker, the RSV *Aurora Australis*, retired from service in 2020. The name RSV *Nuyina* continues this theme and forms another chapter in the story of connection between Australia and Antarctica, in both human and physical terms.

The naming of the RSV *Nuyina* recognises the long connection that Tasmanian Aboriginal people have with the evocative southern lights and the waters to the south of the island. Tasmanian Indigenous people were the most southerly on the planet during the last ice age. The adaptability and resilience of the Tasmanian Indigenous people, who travelled in canoes to small islets in the Southern Ocean, are qualities emulated by our modern-day Antarctic expeditioners as they travel south.

Australian schoolchildren suggested the ship's name through the 'Name our Icebreaker' competition in 2017 that aimed to engage Australian students and expand their understanding of Antarctica; its environment, climate and history; and Australia's role there.

Aboriginal language was the inspiration for one-fifth of all the valid ship names submitted by Australian children. In many of the competition entries, students spoke of their desire for reconciliation with, and recognition of, Australia's Indigenous peoples. Using an Indigenous name for the new ship acknowledges all the children who wanted to recognise the interwoven history of Indigenous people and the great southern land – Antarctica.

Tasmanian Indigenous peoples speak palawa kani today. Development of the language draws on extensive historical and linguistic research of written records and spoken recordings, and Aboriginal cultural knowledge. Since not enough remains of any of the 6–12 original Tasmanian languages to form a full language today, palawa kani combines authentic elements from many of these languages. Language workers used a standard process of linguistic analysis to transcribe early English spellings into phonetics, to compare the sounds. In this way, they could retrieve a language, as close to the original sounds as possible, and reproduce these sounds in the standardised spelling system developed for palawa kani. This language flourishes in Aboriginal community life, and 3 generations of children have grown up learning it. palawa kani features increasingly in public life, including in gazetted Tasmanian placenames.

Photo: © Commonwealth of Australia 2020

Figure 14 Australia's new icebreaker RSV *Nuyina* during sea trials

Assessment Station and human environment

2021

Adequate confidence

Many aspects of the station environment are good. The treatment of waste is good, and remediation of contaminated sites is improving contamination levels. However, the overall footprint is increasing, and fuel use at stations and by vehicles is high and increasing.

Assessment Environmental footprint of stations

2021

Adequate confidence

The human footprint is increasing through modernisation of stations and logistical requirements.

Assessment Waste returned to Australia for landfill

2021

2016

2011

Adequate confidence

The amount of waste returned to Australia depends on the cargo limits of ships and varies from year to year.

Assessment Waste returned to Australia for recycling

2021

Adequate confidence

The amount of waste returned to Australia depends on the cargo limits of ships and varies from year to year.

Assessment Water use

2021

Adequate confidence

The amount of water required varies with the number of people and operational activities.

Assessment Operational fuel use (e.g. generators and boilers)

2021

2016

2011

Adequate confidence

Quantity of fuel used is high but relatively steady at all stations.

Assessment Fuel used by vehicles

Adequate confidence

Fuel use is highly variable at all stations. Increase in fuel use at Casey and Davis stations due to increased activities.

Assessment Electricity

Adequate confidence

Use of electricity is linked to fuel use. The loss of wind turbines increased electricity production by diesel.

Assessment Fuel use by ships

Adequate confidence

Vessels transport goods and people, and undertake marine science voyages. Annual fuel consumption varies, and depends on the number of voyages and sea ice conditions.

Assessment Fuel use by aircraft

Adequate confidence

This is variable from year to year and is dependent on quantities of goods and numbers of people transported by aircraft.

Assessment State of contaminated Antarctic sites

Adequate confidence

Remediation work is continuing and progressing.

Assessment State of listed or specially protected sites in Antarctica and the subantarctic that are managed by Australia

Adequate confidence

Management plans are in place for all protected areas.

Heritage values

Antarctica's unique environment is internationally recognised, and the Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) protects many of its heritage values. 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, historical, aesthetic and/or wilderness values through area protection for specific values, and by adding areas to the list of historic sites and monuments. Whereas environmental, scientific and historical values are relatively easy to define, what constitutes aesthetic and wilderness values has not been defined by treaty parties. A recent study highlighted these issues and attempted to identify wilderness areas by quantifying human activities continent-wide over the past 200 years. One result is that, although 99.6% of the continent can still be defined as wilderness, most areas of biodiversity value have been affected by human activities. Protection of Antarctica's biodiversity would be enhanced by the expansion of the network of Antarctic Specially Protected Areas (ASPAs) (Leihy et al. 2020).

Natural heritage sites

Australia manages 12 ASPAs on the Antarctic continent, including one at Commonwealth Bay, and together with other nations manages the Larsemann Hills Antarctic Specially Managed Area. Since 2015, BirdLife International has identified 41 Important Bird Areas (IBAs) as important breeding sites for flying seabirds and penguins in the Australian Antarctic Territory (BirdLife International 2021). Four ASPAs (Taylor Rookery, Rookery Islands, Scullin and Murray monoliths, and Amanda Bay) are included in this list. A site must fulfil certain criteria identified by BirdLife International to be nominated as an IBA (Harris et al. 2015). The Antarctic Treaty parties agreed to draw on the information about these IBAs in advancing Antarctic environmental protection objectives.

Australia's 2 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 universal value'. The inclusion of these areas on the World Heritage List underlines not only the physical and natural values of these areas, but also their international importance. These areas are also significant for Australia's Antarctic history, and both have sites of cultural heritage value (Parks and Wildlife Service Tasmania & DEST 1996). Heard Island and McDonald Islands is an Australian external territory, managed by the Australian Antarctic Division (AAD). The Heard Island and McDonald Islands Marine Reserve comprises 71,000 km^2 in total, and is classified as a 1A Strict Nature Reserve under International Union for Conservation of Nature categories; its natural values are of outstanding national and international conservation significance (Australian Antarctic Division 2014).

Historic heritage sites

The Mawson's Huts Historic Site at Cape Denison in the Australian Antarctic Territory is Australia's oldest and arguably most significant historic heritage site in Antarctica (Table 7). At the time of their construction, more than 100 years ago, the huts were supposed to last only a few years. Nobody expected that the huts would still be standing more than a century later and considered a valuable part of Australia's Antarctic heritage.

The building materials are vulnerable to deterioration, and the natural elements – wind, weather, frost, ice and meltwater – threaten the integrity of the buildings and structures. Corrosion, fungal growth, wind and snow loads, exposure to ultraviolet radiation, the freeze–thaw cycle, and high relative humidity inside the main hut also affect the conservation of structures and artefacts (Lazer 2006).

The *Mawson's Huts Historic Site management plan* provides guidance for the protection and conservation of the site buildings and artefacts. The Australian Antarctic Division works closely with the Mawson's Huts Foundation, a not-for-profit charity established in 1996, to determine conservation priorities and methods to manage the site appropriately.

On subantarctic Macquarie and Heard islands, artefacts associated with 19th century sealing activities, such as iron melting pots and oil barrels, remain. The maritime climate promotes corrosion of metal artefacts, and windborne sand and salt particles abrade wooden items. Disturbance by wildlife, land erosion and slippage are also potential problems (Vincent & Grinbergs 2002, Clark 2003, Vincent 2004), as are erosion and exposure of artefacts, and volcanic and seismic activities. Seismic activity is a specific threat to structures on Macquarie Island, although most of the research expedition buildings were built to withstand tremors (Lazer 2006). There are several sealers' graves in the south-eastern part of Heard Island, not far from a large king penguin colony. Vegetation cover is dense, and continues to cover and engulf the old graves.

Heard Island is a long way from continental 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 pragmatic management option acknowledges the practical impossibility of conserving all elements of the cultural environment in a remote area with extremely limited access (Vincent & Grinbergs 2002, Lazer 2006). Permitted visits are very infrequent and tend to be restricted to the short summer. The management plan states that heritage values are in a greatly deteriorated state and have been in such a state for a long time and are permitted to disintegrate under the influences of weather and climate. However, the exposed asbestos requires management as it poses a safety risk to people visiting the site.

The AAD liaises closely with vessel operators interested in visiting Heard Island to advise them of permit requirements. Given Heard Island's remote location, however, it is possible that unauthorised visits occur occasionally, and that activities that would otherwise require a permit, such as entering the Heritage Zone or collecting materials from the island, could occur without the awareness of the Australian Government.

A specific risk to Heard Island is the changing coastline. For example, wooden oil barrels left by sealers at Oil Barrel Point have been steadily eroding out of the beach cliff during the past few decades (Lazer & McGowan 1990). Less than a quarter of those recorded in the 1980s are still in place.

Table 7 Status of listings of Australia's historic heritage in Antarctica

Site	National Heritage List	Commonwealth Heritage List	World Heritage List	ASPA/ASMA (designated by ATCM)	HSM (designated by ATCM)
Heard Island and McDonald Islands	Listed 2007	n/a	Registered 1997	n/a	n/a
Macquarie Island	Listed 2007	n/a	Registered 1997	n/a	n/a
Mawson's Huts Historic Site	Listed 2005	Listed 2004	n/a	ASPA 162, designated 2004	HSM 77: Cape Denison, designated 2004
Mawson Station	n/a	Listed 2004	n/a	n/a	n/a
Rock cairn at Proclamation Island	n/a	n/a	n/a	n/a	HSM 3: Enderby Land, designated 1972
Rock cairn at Cape Bruce	n/a	n/a	n/a	n/a	HSM 5: MacRobertson Land, designated 1972
Rock cairn at Walkabout Rocks	n/a	n/a	n/a	n/a	HSM 6: Vestfold Hills, Princess Elizabeth Land, designated 1972
Mikkelsen cairn	n/a	n/a	n/a	n/a	HSM 72: Vestfold Hills, designated 1989

ASMA = Antarctic Specially Managed Area; ASPA = Antarctic Specially Protected Area; ATCM = Antarctic Treaty Consultative Meeting; HSM = Historic Site or Monument; n/a = not applicable

Sources: Department of Agriculture (nd); Antarctic Treaty Secretariat (nd)

Pressures

Climate change

As in other areas of the globe, human activities are directly affecting the climate of the Antarctic region. The 2 key human influences on climate are emissions of greenhouse gases (principally carbon dioxide – CO_2 – methane and nitrous oxide) and substances that deplete the stratospheric ozone layer (chlorofluorocarbons, halons and related gases) (IPCC 2013, WMO 2018, IPCC in press-a).

The increasing atmospheric concentration of greenhouse gases is acting globally to warm the lower parts of the atmosphere and surface. Ozone-depleting substances are also greenhouse gases, contributing to the warming of the lower atmosphere. At the same time, the increasing atmospheric concentration of CO_2 and depletion of stratospheric ozone are acting to cool the upper levels of the atmosphere, as well as the surface of the Antarctic interior (IPCC 2013, WMO 2018). These temperature changes are placing various pressures on fundamental aspects of the Antarctic region, including the structure of the atmosphere, the mass balance of the ice sheet, the formation of sea ice, the availability of liquid water at the surface of the ocean and land, and the physical characteristics of the surrounding ocean.

The extent and rate of change of the climate effects depend on their duration in climate systems (which, in the case of CO_2, amounts to many centuries), and also on the timescale of the long-term changes they cause to the heat content of the deep ocean (which is also expected to be many centuries) (Solomon et al. 2010). International efforts through the Paris Climate Accord are attempting to control greenhouse gas emissions and limit the amount of global warming. The Montreal Protocol has already provided tangible benefits in limiting warming from ozone-depleting substances (Neale et al. 2021).

Air temperature

Whereas the Antarctic interior experiences temperatures well below the freezing point of water throughout the year, coastal areas, particularly in the Antarctic Peninsula region, can experience conditions where ice can melt to provide run-off. Additionally, some areas can experience rainfall. Knowledge of future temperature variability and change is important in anticipating pressures on habitats, such as changes associated with extreme physical conditions, changes in the availability of ice-free areas and sea ice for breeding, and changes in the presence of water for plant growth (Convey & Peck 2019).

Temperatures at the Antarctic surface have shown differing regional patterns of change, with warming in parts of the Antarctic Peninsula and West Antarctica, and generally no significant change in East Antarctica (see Atmosphere). The observed patterns and trends are consistent with influences from changes in the large modes of climate variability, particularly the Southern Annular Mode (SAM) (Turner et al. 2020a). While climate variability is showing the imprint of climate change (Cai et al. 2015, Fogt & Marshall 2020), these modes are also countering the effects of greenhouse warming in some parts of Antarctica. The latest state-of-the-art climate simulations indicate that global warming will have a more significant impact on the Antarctic region during coming decades (Bracegirdle et al. 2020), with the likelihood of increased surface precipitation over coastal areas.

In the stratosphere, ozone depletion in spring influences temperature trends, with cooling observed from the 1980s to around 2000. Subsequently, temperatures have stabilised or slightly warmed (Randel et al. 2017, WMO 2018). Increases in greenhouse gases have also led to cooling in all seasons (Randel et al. 2017, French et al. 2020a), which is strongest in the upper levels (particularly in the mesosphere). In combination with trends near the surface, the changes in the lower stratosphere have altered the thermal structure of the atmosphere, primarily resulting in the strengthening of the westerly wind belt over the Southern Ocean (Polvani et al. 2011).

Winds

The alteration of the temperature structure of the lower atmosphere by climate change has led to a general strengthening of the westerly winds in summer over the Southern Ocean, and a shift in the zone of strongest winds towards Antarctica (Thompson & Solomon 2002, Polvani et al. 2011, Perren et al. 2020). These changes have been implicated in a range of physical effects, including warming in the Antarctic Peninsula region (Turner et al. 2020a); changes in the ability of the Southern Ocean to take up CO_2 (Xue et al. 2018, Keppler & Landschützer 2019); cooling of the surface waters, and warming and freshening below the surface (Kostov et al. 2018, Swart et al. 2018); influences on sea ice (Doddridge & Marshall 2017) and ice-shelf disintegration (Hattermann et al. 2021); and alteration of the overturning circulation in the upper oceanic layers (Li et al. 2019). Increasing wind speeds appear to be promoting regional drying in the Windmill Islands of East Antarctica, and this is implicated in the degradation of moss communities (Robinson et al. 2018, Bergstrom et al. 2021).

Over the next few decades, the wind changes over the Southern Ocean are likely to be held in place due to competing effects – long-term cooling of the stratosphere from increasing greenhouse gases and the warming associated with increasing ozone concentrations as the ozone hole recovers (Arblaster et al. 2011). Increasing greenhouse gas concentrations are expected to cause general strengthening of the westerly winds in all seasons (Morgenstern 2021).

At the Antarctic coast, the easterly surface winds are expected to weaken over the coming decades in response to changes in the strength and position of the westerlies over the Southern Ocean (Bracegirdle et al. 2020). Additionally, the northward penetration of the katabatic winds away from the coast is likely to be reduced as a result of surface warming and strengthening of the SAM (Bintanja et al. 2014).

Although changes in surface wind direction and speed have potential implications for coastal and marine habitats in the Antarctic region, it is not clear how expected future wind changes will affect certain species. For example, Fretwell & Trathan (2020) concluded that the emperor penguin is susceptible to changes in wind regime. On the other hand, Antarctic seabirds have shown some tolerance to variability in present wind conditions.

Precipitation

Precipitation, in the form of falling snow, ice crystals, hail and rain, is a potential stressor of animals and plants in the Antarctic region (Convey & Peck 2019) as it can influence heat loss, and the physical properties of nesting and breeding habitats. On the other hand, the cold Antarctic climate limits the availability of liquid water, and plants especially can benefit from rain and melting ice.

Precipitation has shown mixed patterns of change in the Antarctic and Southern Ocean region, reflecting influences from large-scale modes of climate variability, including the El Niño–Southern Oscillation and the SAM (Turner et al. 2014, Turner et al. 2020a). Parts of the Antarctic Peninsula and West Antarctica have shown evidence of a positive trend in the observational period (Turner et al. 2005a), while trends in East Antarctica are generally not significant (Bromwich et al. 2011).

Changes in local precipitation can affect biological communities. For example, regional drying in the Windmill Islands of East Antarctica is implicated in the degradation of moss communities (Robinson et al. 2018). In contrast, growth has increased in plant communities on the Antarctic Peninsula as a result of precipitation increases and warming (Amesbury et al. 2017). Altered wind and precipitation patterns are causing extensive change in the alpine tundra (fellfield) ecosystem on Macquarie Island, with the collapse of endemic keystone species, such as the Macquarie cushion plant and associated bryophytes (Bergstrom et al. 2015, Bergstrom et al. 2021). Future projections suggest generally increased precipitation in Antarctica (Bintanja et al. 2014, Bracegirdle et al. 2020), with possible benefits for microflora (Singh et al. 2018), but negative effects on some penguin species (Bricher et al. 2008, Trathan et al. 2015). For example, Adélie penguins at Pointe Géologie, East Antarctica, suffered major breeding failures in 2013–14 when rain flooded nests, and downy chicks whose plumage is not yet waterproof died of hypothermia and starvation (Ropert-Coudert et al. 2015).

Ultraviolet radiation

The stratospheric ozone layer protects the biosphere from harmful levels of solar ultraviolet radiation (UVR). The development of the Antarctic ozone hole in the late 1970s (WMO 2018) has increased the exposure of large regions of Antarctica and the Southern Ocean to UVR, primarily in spring. Several studies have identified biological impacts in the Antarctic region from increased radiation exposure, including cellular damage in algae (Davidson & Belbin 2002), sea urchins (Schröder et al. 2005) and plants, including mosses (Newsham & Robinson 2009, Turnbull & Robinson 2009); reduced survival of krill larvae (Ban et al. 2007); and effects on human health (Russell et al. 2015, Neale et al. 2021).

Over the coming decades, the ozone hole will continue to recover as a result of international controls imposed on ozone-depleting substances by the Montreal Protocol (WMO 2018); full recovery (defined as a return to 1980 conditions) is expected by around the middle of the 21st century (Dhomse et al. 2018, Amos et al. 2020). Accompanying the recovery, the UVR-induced biological stress caused by ozone depletion in the Antarctic region will subside. Towards the end of the 21st century, the speedup of the equator-to-pole circulation driven by global climate change (WMO 2018) will additionally increase the total ozone column in the Antarctic region, and lead to further reduced UVR exposure compared with conditions during the ozone hole era.

Sea ice

Any substantial changes in Antarctic sea ice coverage, thickness and properties have wide-ranging consequences and may have major impacts on global climate, regional weather, ocean properties and processes, ecosystems, biogeochemical cycles, sea level rise and human activities (Massom & Stammerjohn

2010). For example, the krill fishery at the Antarctic Peninsula is now mainly active in autumn and winter rather than in midsummer (Meyer et al. 2020).

Numerous plant and animal species depend on sea ice as a food source, shelter, refuge and breeding platform, and are highly adapted to its presence and seasonal rhythms (Massom & Stammerjohn 2010). These organisms range from microscopic primary producers (e.g. ice algae) that proliferate in high concentrations within the icy matrix (Arrigo et al. 2017) and support pelagic herbivores such as krill (a keystone species that also supports major fisheries (Bluhm et al. 2017)), through to fish, seals, seabirds (including penguins) and whales (Ainley et al. 2017, Bester et al. 2017). Sea ice also controls the amount of light that is available to photosynthesising organisms within the upper water column (Clark et al. 2015). Each late spring to summer, seasonal sea ice melt releases a pulse of algae, fresh water and key nutrients that have accumulated within the ice to drive intense algal blooms around the high-latitude Southern Ocean. Sea ice algae released into the water column also form a primary food source for biodiverse benthic (seabed) ecosystems in shallow nearshore Antarctic regions (Clark et al. 2017).

There is low confidence in climate model projections of the trajectory of Antarctic sea ice in coming decades in a warming world (IPCC in press-a). However, there is general agreement across model projections that substantial decreases in Antarctic sea ice extent and volume will occur by 2100 in response to climate change. Estimates of predicted decreases in sea ice area range from 29% to 90% in February (depending on the emissions scenario) and from 15% to 50% in September (Roach et al. 2020). The implications of these changes for the food webs of the Southern Ocean and Antarctic coastal environments are currently not well understood (Newman et al. 2019).

Ocean temperature

The Southern Ocean has warmed more rapidly and to a greater depth than the global ocean average in recent decades (Böning et al. 2008, Roemmich et al. 2015, Swart et al. 2018). Increased ocean heat transport has caused Antarctic ice shelves and glaciers to thin and retreat (Jacobs et al. 2012, Stevens et al. 2020), particularly in West Antarctica (Joughin & Alley 2011, Rignot et al. 2014). Melting of grounded ice, as well as thermal expansion of the ocean due to warming, contributes to global sea level rise (IMBIE team 2018).

As water temperature increases, its ability to absorb CO_2 decreases. Thus, increased ocean temperatures reduce the important role of the ocean as a carbon sink, leaving more greenhouse gases in the atmosphere and driving further global warming (Menzel & Merlis 2019).

Ocean acidification

The world's oceans have taken up around 25–30% of the anthropogenic (human) CO_2 released to the atmosphere. Some 40% of these emissions have been taken up by cold Southern Ocean waters that lie south of 40°S (Rintoul 2018, IPCC in press-a), altering its ionic content. The uptake of CO_2 varies with season and location, resulting in non-uniformity in the vertical structure of carbon storage in the Southern Ocean (Rae et al. 2018). Current atmospheric CO_2 levels, at more than 400 parts per million by volume (NOAA 2021), are higher than they have been for the past 80,000 years (see Figure 6 in case study: Vulnerability of the Antarctic ice sheet to future climate change), and even the past 25 million years (Noble et al. 2020). Compared with pre-industrial times (before the 1700s), when CO_2 levels were around 280 parts per million, the pH of the Southern Ocean has dropped from pH 8.2 to pH 8.1 as a direct result of CO_2 uptake (ACE CRC 2010). Although the ocean is still alkaline, it is becoming more acidic in a process known as ocean acidification. Because the pH scale is logarithmic, the 0.1 change means that the acidity of the ocean has increased by 30%.

Ocean acidification is likely to have profound impacts on Antarctic marine species and ecosystems if it continues to increase at current rates (Doney et al. 2009, Hancock et al. 2020). Human food security and economies may also be affected (Doney et al. 2020). Although some marine species may be resilient (Peck et al. 2018), organisms that have evolved under comparatively stable conditions are expected to be vulnerable. Ocean acidification is already affecting many ocean species, especially organisms such as oysters and corals that make hard shells and skeletons by combining calcium and carbonate from seawater (IPCC in press-a). As ocean acidification increases, fewer carbonate ions are available for calcifying organisms to build and maintain their shells, skeletons and other structures. If the pH becomes too low, shells and skeletons can begin to dissolve (Hancock et al. 2020).

The physiology and energy requirements of shelled organisms, such as pteropods and molluscs, may also be negatively affected (Seibel et al. 2012). Changes in the carbon chemistry of the oceans can reduce the growth rate of the larvae of some fish species, and affect their respiration and behaviour. Larval fish and other marine organisms lack the ability to self-regulate their internal pH. Increases in environmental CO_2 concentration can lead to decreases in internal pH, which can cause behavioural and developmental issues and even death (Hancock et al. 2020, Brasier et al. 2021).

Population

As the only continent without a native human population, Antarctica has experienced 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.

Pollution

Despite the large distances separating Antarctica from the rest of the world, pollution is present in Antarctica, whether from legacy or contemporary station operations, or transported from other continents by air or water.

Pollution from stations

Emissions from exhausts of machinery, oil spills, sewage outfalls and abandoned tip sites are all primary sources of hydrocarbon and heavy metal contamination in Antarctica (Stark et al. 2016, Raymond et al. 2017, Chu et al. 2019).

The Australian Antarctic Division's Environmental Management System supports a reduction in pollution from stations during the planning, operational and continual improvement stages. Recent incident and hazard reporting has resulted in actions to reduce emissions from incineration of waste, and has improved fuel spill response and spill vigilance by expeditioners.

Waste

Contaminated waste disposal is a product of past practices of Antarctic expeditions. Before the Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) was signed in 1991, rubbish was dumped at various locations near the stations, or was disposed of by leaving it on the sea ice until it broke out, which resulted in waste and contaminants entering the terrestrial and marine environments.

Some contaminants are present in quantities known to be hazardous to the environment. Although frozen for much of the year, these contaminants, either dissolved in water or attached to sediment, can be mobilised during the summer months when there is increased water flow through contaminated areas from snowmelt.

The Environmental Aspects and Impacts Register identifies waste-management impacts and associated mitigation measures required to minimise waste at the activity level.

Fuel

Each of Australia's permanent stations has an oil spill contingency plan. This is a requirement of Article 15 of the Protocol on Environmental Protection to the Antarctic Treaty. Any ship owned or chartered by the Australian Antarctic Program also must have a current contingency plan. Depending on their role, any expeditioners participating in major fuel transfer receive basic or specialist training. However, accidents happen.

The largest ongoing risk and source of new pollution in Antarctica is associated with storing and handling bulk volumes of fuel. As part of the Australian operations, large quantities of Special Antarctic Blend fuel (more than 1 million litres (L) per station per year) are transferred from a ship, and stored and handled at the stations. The climate in Antarctica presents significant challenges for infrastructure and operations. There is always the risk of spills when transporting, handling or storing fuel. Land-based fuel spills, some as large as 15,000 L, have occurred in the past, because of mechanical failures or human error during transfer from ship to shore or transfer between storage tanks and powerhouses.

Fuel spills occurred, mainly caused by equipment failure but also by human error. The effect of one oil spill of 4,000 L was rated as high, and the effect of another of just over 1,000 L as medium (DEE 2019). Half of all recorded spills were 10 L or less, and 85% were less than 200 L, the official reporting level for spills of the Committee of Managers of National Antarctic Programs (COMNAP) (COMNAP 2008).

At times, fuel storage tanks, valves and piping have leaked during winter, and the leaks have gone unnoticed until the summer melt revealed that these storages had drained their contents. Today, all tanks are bunded (surrounded by a secondary containment that minimises or eliminates any fuel leakage from fuel storage areas). Hence, the environmental damage is reduced or avoided altogether. However, not all fuel infrastructure (e.g. fuel transfer pipework, flanges, pipe joins) has secondary containment.

At Davis and Casey stations, the Australian Antarctic Division (AAD) has successfully remediated soils contaminated from several fuel spill events at the bases, and used remediated soils in local building projects (McWatters et al. 2016b). Recently, several tip sites and old fuel spill sites have been assessed and remediated. At the time of writing, the most significant fuel spill remediation underway is of contaminated soil and water at 4 spill sites at Casey Station; 2 of these incidents occurred in 2015 and 2018 when a connection in the fuel transport infrastructure leaked and contaminated the site.

Another potential source of fuel contamination derives from empty fuel drums. If left in situ, they will eventually rust, and residual fuel will leak into the environment. In the 2014–15 season, the AAD removed 2,600 crushed steel drums (weighing nearly 50 t) from Davis Station for recycling in Australia (Greenslade et al. 2008).

These incidents have been the subject of root-cause investigations, and comprehensive assessment and remediation planning have been conducted to identify the best course of action in containing and remediating the site. A major theme of Australia's Antarctic Science Program is scientific and engineering research to understanding, assess, remediate and monitor human impacts. Further strategic planning for assessment and clean-up of contaminated sites within the Australian Antarctic Territory is a key deliverable of the 2016 Australian Antarctic Strategy and 20 Year Action Plan (Australian Antarctic Programme 2016).

Building materials

Some station buildings contain asbestos and are listed in the AAD's asbestos register. The AAD is addressing this hazard and is progressively removing asbestos from its buildings. For example, the former living quarters at Davis Station contained a significant quantity of asbestos. This was removed and returned to Australia in 2015.

Other areas, such as Heard Island, present a greater challenge. The decay of buildings and structures, and the extent of asbestos debris on the island were assessed in 2012. However, there has not yet been an opportunity to undertake any clean-up activity at the site of the former Australian National Antarctic Research Expeditions station at Atlas Cove on Heard Island. The AAD provides warnings and advice to government and nongovernment operators intending to visit the site, as part of the permitting process provided for in the *Heard Island and McDonald Islands Marine Reserve management plan*, and the Environment Protection and Management Ordinance 1987 to the *Heard Island and McDonald Islands Act 1953.*

Pollution from global sources

Pollution and toxins can arrive in Antarctica from all over the world. Plastics can travel on ocean currents. Winds can transport volatile substances into distant areas, and pollutants with a long atmospheric residence time can disperse on a global scale (GESAMP 2001).

Plastics

Plastic pollution due to unsustainable use and disposal of plastics is a serious threat to the environment and human health. This is an area of international research through the SCAR Action Group on Plastics in Polar Environments.

Plastics increasingly contribute to environmental pollution both on land and at sea, and endanger wildlife (Waller et al. 2017). Although the Southern Ocean is still comparatively unpolluted, some subantarctic regions – particularly in the Indian Ocean – are becoming increasingly exposed to plastic pollution (Perold et al. 2020).

Entanglement in plastics, such as ropes, nets and monofilaments used in commercial fishing operations, threatens at least 243 species. Entanglement often results in death and may be responsible for most plastic-related deaths. For example, young Antarctic fur seals (*Arctocephalus gazella*) can become caught in plastic materials; as the animals grow, the plastic tightens and cuts into their bodies (Pemberton et al. 1992). As plastics persist for years in the environment and do not decompose, they can kill repeatedly once the carcases of entangled animals have decomposed (Mattlin & Cawthorn 1986).

There are concerns about an increase in plastic waste at high latitudes, particularly with regard to seabirds that frequently ingest marine plastic debris (Wilcox et al. 2015, Kühn et al. 2021). Plastics are also ingested by marine predators, either directly when they forage (primary ingestion) or indirectly when they receive it from contaminated prey species (secondary ingestion). A long-term study at Marion Island, in the southern Indian Ocean, documented a decrease in fisheries-related plastics as fishing activities in the region decreased after 1999, but noted a near-simultaneous increase in other litter. Matter regurgitated by wandering and grey-headed albatrosses, and giant petrels contained food packing, plastic bags and rubber gloves (Perold et al. 2020).

Near Antarctic stations, plastic ingestion has been noted, for example, in 9% of brown skuas (*Stercocarius antarcticus lonnbergi*) at Esperanza Bay, Antarctic Peninsula (Ibañez et al. 2020). At Haswell Island, East Antarctica, a 23 cm piece of synthetic rope (possibly a snood from a fishing line) was discovered in the stomach of an emperor penguin chick. The rope probably did not cause the death of this chick (Golubev 2020). However, among petrels, up to 63% of deaths were due to ingestion of plastics (Rochman et al. 2016). Small petrels are particularly at risk of dying when plastics become lodged in their digestive systems, while large petrels and albatrosses may pass on the contaminants to their chicks (Petry & Benemann 2017).

In addition to macroplastics, microplastics (less than 5 mm) are of concern as they spread through the food web. For example, at Macquarie Island, microplastics were isolated from fur seal scats, the result of secondary ingestion of big-eye lantern fish (*Electrona subaspera*) (van den Hoff et al. 2018). As filter feeders, baleen whales also ingest microplastics directly (Besseling et al. 2015).

Toxins

Heavy metals occur naturally in the environment and can be transported via sea-spray, windblown dust and volcanism (Dick 1991). Industrial and agricultural contaminants have reached Antarctica through global circulation (Chu et al. 2019). Organochlorine pesticides such as hexachlorocyclohexanes (HCHs) and other persistent organic pollutants (POPs) travel large distances through the atmosphere (Corsolini et al. 2002). Some chemicals can reach the polar regions through a process known as ‘global distillation’: volatile chemicals evaporate in the warmer places where they are used and condense in colder places to which they are transported (Mackay & Wania 1995, Yamashita et al. 2018, Bertinetti et al. 2020).

Airborne pollutants can be deposited into the ocean and land environments, where they may enter the food web. For example, dichlorodiphenyltrichloroethane (DDT; a synthetic pesticide once widely used) and its derivatives bind to particles in water and to organic matter where they remain for many years. Since POPs accumulate in phytoplankton, they enter the food web at its very base (Chiuchiolo et al. 2004). Plankton (krill, copepods and fish larvae) ingest the pollutants, which accumulate in their fatty tissue. Since toxins are not digested, seabirds and marine mammals acquire them through their diet, and the toxins are concentrated through the food web (a process called bioaccumulation) (Corsolini et al. 2002). As part of their adaptation to life in the extreme cold, Antarctic organisms often have high levels of fats, which can result in the bioaccumulation of fat-soluble toxins (Corsolini et al. 2017). For example, POPs have been isolated from the blubber of fin whales (Taniguchi et al. 2019). Biopsied tissues taken from fin whales feeding near the Antarctic Peninsula contained hexachlorobenzene (HCB; a fungicide), DDT and derivatives, HCHs and polybrominated diphenyl ethers (PBDEs). DDT levels were 15–380 times higher than in specimens collected in the Northern Hemisphere. PBDE levels were similar to samples from the

Northern Hemisphere, whereas HCH content was lower (Taniguchi et al. 2019).

An issue of concern is that fat-soluble (lipophilic) pollutants accumulate in the tissues of female whales. Many species spend the austral summer in the Southern Ocean where they feed extensively before they head north to their breeding grounds. During their migration and breeding time, the whales often undergo periods of fast. Toxins stored in the mother's fat become mobilised and can also be transferred to the embryo and calf. The impacts of this on the whales' immune function, for example, need urgent attention (Nash 2018).

As early as the 1960s, traces of DDT were detected in the fat tissue of Adélie penguins (George & Frear 1966). In 1978, DDT and its derivatives were found in tissues and eggs of 3 species of brush-tailed penguins (*Pygoscelis* spp.) on the Antarctic Peninsula (Łukowski 1983). The Stockholm Convention on Persistent Organic Pollutants banned the use of this pesticide for general agricultural use in the Northern Hemisphere in the 1970s, and worldwide in 2001. Some countries still produce and use DDT to fight malaria; in 2014, some 3,772 t were produced globally – a 30% decrease since 2001 (van den Berg et al. 2017). In 2010, DDT still occurred in the feathers of Adélie and gentoo penguins (Metchava et al. 2017).

POPs, including DDT, have also been detected in 5 lakes in the Larsemann Hills, East Antarctica (Bhardwaj et al. 2019), and DDT, HCHs, HCB and polychlorinated biphenyls (PCBs) were found in the soils and some lichen on the coast of East Antarctica (Negoita et al. 2003). DDT was also detected in the muscle tissue of Antarctic toothfish in the Ross Sea at relatively high levels (20.1 ± 6.70 nanograms per gram wet weight). These fish are relatively slow-growing, long-lived predators (living to around 50 years). Thus, toxins can potentially accumulate in their tissues for decades. Weddell seals, predators of Antarctic toothfish, also had elevated levels of DDT in their livers (Corsolini et al. 2017).

A number of new POPs have been reported from Antarctica, including polychlorinated naphthalenes (PCNs), hexabromocyclododecanes (HBCDs), and polychlorinated compounds such as Dechlorane Plus (DP) and related compounds (Kim et al. 2021). It is currently unknown how far they are spread; PCNs have so far only been reported from the Ross Sea (Grotti et al. 2016). However, this is due to a paucity of studies. Dechlorane Plus is a flame retardant for plastics that is added, for example, to the coating of electrical wire and cables, used in TV connectors, and is also used in computer screens (Persistent Organic Pollutants Review Committee 2020). DP appears to cause metabolic and developmental disorders in animals (Kim et al. 2021) and is currently under consideration for listing under the Stockholm Convention. Brominated flame retardants were recently detected in the soil of Adélie penguin colonies in East Antarctica (Lewis et al. 2020).

In various regions of Antarctica, mercury, lead, cadmium and other metals have been isolated from many different organisms, such as penguins (Jerez et al. 2013, Pacyna et al. 2019), flying seabirds (Tartu et al. 2015, Becker et al. 2016, Souza et al. 2020), various marine invertebrates (Webb et al. 2020), lichens and mosses(Zvěřina et al. 2014), and yeasts (Fernández et al. 2017a). Phenol-degrading yeasts are tolerant of heavy metals and may find a use in the treatment of wastewater in cold environments (Fernández et al. 2017a).

The 4 penguin species at Macquarie Island all had traces of mercury in their feathers. The levels in 2002–03 were significantly different in all species from historical values (1937–76). Although mercury levels had decreased in king and royal penguins, they had increased in gentoo and rockhopper penguins. Variability in diet and foraging strategies may explain interspecific differences, but the reasons for the different trends are still unclear (Gilmour et al. 2019).

Metal contamination can be a problem in the nearshore environments of stations. Various metals, such as chromium, iron, nickel and zinc, are essential for the maintenance of healthy function. However, when these so-called trace elements surpass a certain threshold, they can become toxic. In marine algae, for example, metal uptake from the environment is highly regulated. However, when different metals occur together at elevated levels, they may affect an organism differently from when they occur by themselves. For example, 2 Antarctic marine microalgae – *Phaeocystis antarctica* and *Cryothecomonas armigera* – were exposed experimentally to cadmium, copper, nickel, lead and zinc to examine toxicities of the metal mixture compared with a single metal. Both algae accumulated metals in their cells; copper appeared to drive toxicity, whereas zinc appeared to provide some protection from toxicity of the other metals. Depending on the mixture and relative concentration of the various metals, there is a risk of bioaccumulation of metals and potentially toxicity in the Southern Ocean food web at the level of microalgae and grazing plankton (Koppel et al. 2019).

Large-scale processes underlie the presence of POPs in Antarctica. The best-studied component is probably DDT and its derivatives. Penguin samples collected over the past five decades show that the concentration of dichlorodiphenyldicholoroethylene (DDE), a derivative of DDT, rose from the 1960s, peaked around 1985 and has steadily declined since (Ellis et al. 2018). The decrease of POPs in the Southern Ocean may indicate that these compounds have left the pelagic environment and have entered the benthic realm. As part of the biological carbon pump, POPs bound to organic matter, such as moulted exoskeletons of krill or faeces expelled by vertebrates while at sea, sink to the ocean floor and accumulate there (Ellis et al. 2018). Antarctica provides an important site for monitoring global background levels of known contaminants controlled by the Stockholm Convention (SSC 2020), and marine sediments and benthic communities may need to be examined to assess levels of POPs and other pollutants.

Industry

A small number of industries have direct impacts in Antarctica.

Commercial fishing

Antarctica is a productive fishing ground that is used by many countries. Mid-water trawlers and continuous fishing system vessels catch krill, while predominantly longline vessels catch toothfish. There is some bottom trawling in areas of national jurisdiction for toothfish and icefish. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) manages the fisheries in the Convention Area of the Southern Ocean – which is divided into 3 statistical areas, several subareas, divisions and subdivisions (Figure 15) – and sets catch limits for each fishery and each area, open and closed season periods, move-on rules and measures to minimise bycatch. Each vessel eligible to fish commercially participates in a race to obtain as much krill or fish until the total catch limit is reached, and the fishery is closed. CCAMLR allows the allocation of a specific catch for a member in some specific areas to conduct research or exploratory fishing (Reid 2019).

Krill fishing

The Antarctic krill fishery is the largest commercial fishery in the Southern Ocean. However, there is currently no krill fishery off East Antarctica. The krill fishery is concentrated in the South Atlantic Ocean (Statistical Area 48; 3.45 million square kilometres). Most of the catch is taken using a continuous fishing system that pumps krill nonstop from the codend of the net onto the ship, rather than hauling the catch aboard in a net. The continuous fishing system has been employed since 2004 by Norway and more recently by China. CCAMLR sets catch limits for different areas in the Southern Ocean; catch limits vary from 93,000 to up to 279,000 tonnes (t) per managed area. Antarctic krill was first fished at low levels in the 1960s (4 t in 1961–62 and 306 t in 1964–65) as an exploratory fishery (Miller & Agnew 2000). Commercial exploitation began only in late 1973; at this time, annual catches amounted to around 500,000 t of Antarctic krill (Nicol et al. 2012).

The total catch limit for Area 48 (30°E to 70°W) is 5.61 million tonnes. However, since commercial fishing has increasingly concentrated on a much smaller area, targeting only a section of the whole krill population, there were concerns that the concentrated fishing activities would have a disproportionate effect on local krill populations, associated ecosystems and krill-dependent predators. Therefore, in 1991, CCAMLR implemented interim precautionary catch limits for large statistical areas. These ‘trigger limits’ in an area cannot be exceeded until a more elaborate management strategy is established. For Area 48, the trigger limit was set at 620,000 t; this limit will be in place until catch effort can be distributed relative to the total krill population (Reid 2019). An interim measure is currently in place to distribute the trigger limit across the 4 subareas. Since 2015, the fishery in Subarea 48.1 was closed to krill fishing before the end of the fishing season on 3 occasions, because the catch had reached annual trigger limits.

Since 2005, krill catches in Area 48 have steadily increased but have remained below the total catch limit. Since 2013, the catch limit of 155,000 t has been reached in Subarea 48.1, where catches by conventional trawlers were 46% higher in 2019 than in 2008. Vessels with a continuous fishing system can operate in the Antarctic krill fishery. Around 450,000 t is being harvested in total from Area 48. In the 2019–20 CCAMLR fishing season, the krill catch in Area 48 was the highest in the recorded history of the fishery (CCAMLR 2021b).

Off the western Antarctic Peninsula, krill catches have increased over the past 2 decades, particularly in the Gerlache and Bransfield straits. The krill fishery is active during the breeding season of gentoo and chinstrap penguins. The interactions between the fishery and penguins are complex and dependent on environmental conditions. For example, low levels of sea ice can reduce krill recruitment in some years. Furthermore, the SAM index plays a role (see Atmosphere). In years when it is negative, the probability of lowered breeding success increases (see Watters et al. (2020)) Also, the recovery of populations of baleen whales may increase competition for resources (Krüger et al. 2021).

In East Antarctica, krill fishing took place from 1974 to 1995 (Williams 1985, Pauly et al. 2000). After many years of no krill fishing, small krill catches have been taken again since 2017. Krill fishing is likely to intensify in East Antarctica. There is currently a catch limit of 440,000 t in place for Division 58.4.1, split into 2 areas, and a catch limit of 260,000 t for Division 58.4.2 (CCAMLR 2017).

So far, CCAMLR has successfully managed the krill fisheries. The organisation has carefully monitored the quantity of krill caught at any one time (catch capacity), and the quantity of krill that can be taken in a season. However, the development of new technologies and the arrival of new entrants into the fishery must be managed carefully (Nicol & Foster 2016). If the ratio of the catch capacity to total allowable catch is low, it is possible to monitor catches and forecast potential closures. However, as catch limits are being reached faster (e.g. through continuous fishing), it becomes more challenging to make these forecasts and keep fishing activities within the catch limits. Given the large scale over which the fishery operates, it is also challenging to conduct fishery-independent surveys of krill stocks. For example, broadscale surveys in Area 48 have occurred with an interval of 20 years (2000 and 2019) (Trathan et al. 2001, CCAMLR 2019). Developments are underway to involve commercial vessels in collecting data that can support more regular assessments.

The krill fishery may also face challenges associated with the vulnerability of krill to environmental changes, particularly climate change (Kawaguchi et al. 2013). Changes to the marine environment are having a significant impact on krill. Increasing ocean acidification is likely to affect krill embryos negatively and may significantly reduce hatching success (Kawaguchi et al. 2013, Veytia et al. 2020). Since krill is near the base of the food web, these changes may have profound effects throughout Antarctic ecosystems, particularly on dependent predators such as seabirds, seals and whales. The challenge is thus to manage krill fishing while achieving ecosystem-based objectives (Reid 2019).

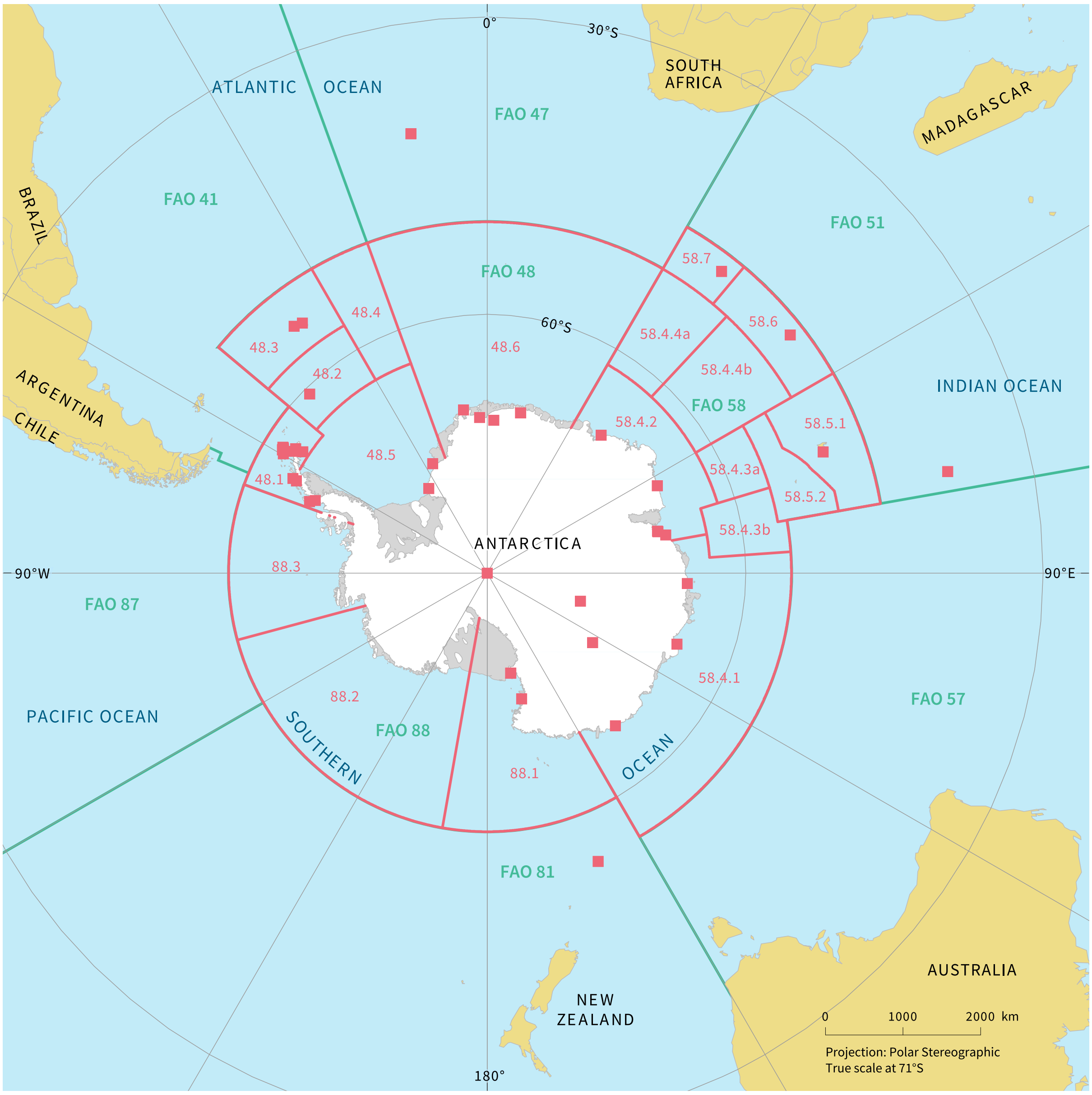
Fishing for fin fish

The dominant target species of fin fish in Southern Ocean fisheries are toothfish (*Dissostichus* spp.). The estimated aggregated weights of toothfish caught in 2018 and 2019 were 30,591 t and 30,231 t, respectively. Australia was the second largest producer after France (CCAMLR 2021a). The precautionary approach to fisheries management taken by CCAMLR, with set catch limits and comprehensive regulations in place, is highly unlikely to have a negative effect on Southern Ocean ecosystems. Current levels of illegal, unreported and unregulated (IUU) fishing in the CCAMLR area are at a historical low. However, the high value of toothfish and the difficulty of comprehensive surveillance of the vast Southern Ocean remain a strong incentive to IUU fishers (see Illegal, unreported and unregulated fishing).

In the Southern Ocean, in East Antarctica Divisions 58.4.1 and 58.4.2, commercial fishing operations have remained well below set catch limits because only small-scale, exploratory fisheries currently operate in Division 58.4.2 (Table 8).

In Australian subantarctic waters, commercial fishers harvest Patagonian toothfish (*Dissostichus eleginoides*) and, to a lesser extent, mackerel icefish (*Champsocephalus gunnari*). Australian fishing efforts are concentrated around the subantarctic Heard Island and McDonald Islands, and Macquarie Island. Substantial marine reserves surround both regions. Precautionary catch limits and various other environmental controls apply in accordance with CCAMLR's conservation measures (see Convention on the Conservation of Antarctic Marine Living Resources). The toothfish fisheries are relatively small, landing less than 5,000 t per year.

Except in 2015, only 1 vessel has been licensed to catch mackerel icefish at Heard Island since 2007. Catch limits have varied since the inception of this fishery in 1997 due to the high recruitment variability of this species (Maschette & Welsford 2019). For example, the catch limit was 2,980 t in 2003; this has decreased to around 500 t since 2016. In 2020,



Year-round station — CCAMLR Statistical Reporting Subarea boundary — FAO Fishing Area boundary

Ice shelf, ice tongue — Continental ice — Country

CCAMLR = Commission for the Conservation of Antarctic Marine Living Resources; FAO = Food and Agriculture Organization of the United Nations; km = kilometre

Source: Australian Antarctic Data Centre

Figure 15 CCAMLR statistical reporting area and subarea boundaries, and FAO fishing area boundaries the vessel landed 507 t, only 20 t short of the year's catch limit (Table 8) (CCAMLR 2021c).

As the summer sea ice is receding in some areas such as the Antarctic Peninsula, certain regions are becoming more accessible to fishing vessels. Thus, the krill fishery has remained on the fishing grounds later into the autumn and winter (CCAMLR 2021b).

The Australian Fisheries Management Authority (AFMA) regulates the fishing activities of Australian vessels, consistent with CCAMLR conservation measures. AFMA also manages the fishery around Macquarie Island. Although it falls outside the CCAMLR area, CCAMLR-like procedures apply here as well. Licensed vessels in the subantarctic fisheries show a very high degree of compliance with licence conditions. Based on the best scientific information available, catch limits are adopted through the CCAMLR process, and Australia undertakes regular fish stock assessments for the regions. The tight regulation of fishing permits and the requirement for comprehensive mitigation methods have virtually eliminated seabird bycatch in these regions.

Fishing and other legal or illegal extraction of resources are themselves pressures on the Antarctic environment and its species. Other pressures affecting the fisheries include the impacts of climate change (particularly ocean acidification), and other anthropogenic factors, such as pollution.

Strategies are needed to protect the marine food web – for example, through establishment of more marine reserves. Currently, CCAMLR marine reserves exist off the South Orkney Islands near the Antarctic Peninsula, and in the Ross Sea region. Furthermore, CCAMLR and Australia need to examine more formally the current and future impacts of climate change on Southern Ocean ecosystems. For example, climate change scenarios could become part of decision rules that are used to estimate catch limits (Brooks et al. 2018).

Table 8 Australian Antarctic fisheries catches and catch limits, 2015–20

	Catch (catch limit) (tonnes)		
Season	**Antarctic toothfish Area 58.4.1**	**Antarctic toothfish Area 58.4.2**	**Mackerel icefish Area 58.5.2**
2015	122 (724)	10 (35)	10 (309)
2016	400 (660)	Not fished	469 (482)
2017	206 (660)	35 (35)	543 (561)
2018	264 (545)	42 (42)	515 (526)
2019	Not fished	50 (50)	443 (443)
2020	Not fished	58 (60)	507 (527)

Source: CCAMLR (2020)

Illegal, unreported and unregulated fishing

IUU fishing encompasses all fishing and related activities that breach any law (national or international) with regard to extraction, reporting and conservation (Ma 2020). In the areas managed by CCAMLR and Australia, IUU fishing has effectively been reduced to near zero in recent years. In the absence of actual catch rates, it is difficult to determine how much fish IUU vessels catch.

As well as harming fish stocks through overfishing, including in prohibited areas, IUU activities are frequently linked to arms, people and drug smuggling activities; bribery; money laundering; and document fraud (Swan 2018). In 2016, the Food and Agriculture Organization of the United Nations brought into force the Agreement on Port State Measures, a legally binding agreement, to prevent illegally caught fish entering markets (FAO 2021).

All known IUU vessels have used gillnets, a method that CCAMLR has banned. Lost gillnets continue to float through the ocean, and catch and destroy fish ('ghost fishing'), so that the actual numbers of fish taken from the ecosystems are much larger than those officially reported.

Historically, bottom longline and gillnet IUU fishers have exploited toothfish on the continental slope and submarine banks. Since 2009–10, CCAMLR has not estimated IUU fishing at the level of individual stocks. However, the organisation maintains a list of IUU vessels of both contracting and noncontracting parties.

Off the coast of East Antarctica, IUU fishing is at historically low levels. However, as fisheries productivity in low and mid-latitudes are predicted to decrease because of climate change, IUU fishing may return to higher latitudes. If it were to resume, uncontrolled fishing is likely to alter the structure of the Southern Ocean food web and could lead to stock declines (Trebilco et al. 2020). Thus, the ecosystem-based management approach used by CCAMLR would be jeopardised.

Tourism

Tourism is a major economic activity in Antarctica and is regulated under the Antarctic Treaty, its Protocol on Environmental Protection, and measures and resolutions adopted by the Antarctic Treaty Consultative Meeting. In addition, regulations of the International Maritime Organization (IMO) determine standards for ship operations. It is mandatory for all shipping operators to adhere to the IMO's International Code for Ships Operating in Polar Waters (Polar Code), which entered into force on 1 January 2017 (IMO 2019). The requirements of the Polar Code supplement those of the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL), which still apply to polar shipping. The Polar Code aims to protect human lives, but also to minimise the impact of shipping on polar environments (IMO 2019).

Antarctica is a popular tourist destination, and the industry continues to grow. From 2014–15 to 2019–20, the number of visitors more than doubled, increasing from 36,702 to 74,381 (IAATO 2021). Most tourists visited the Antarctic Peninsula; some travelled to the Ross and Weddell seas regions. On the Antarctic Peninsula, the number of sites visited increased from 206 in 2014–15 to 282 in 2019–20 (IAATO 2021). From 2018–19 to 2019–20, tourist numbers increased by 32% from 56,168 to 74,401 visitors (Carey 2020, IAATO 2021). The increase was in part due to the launch of 9 new purpose-built vessels (IAATO 2021).

In East Antarctica, the Ross Sea is the most visited region, but the cost and duration of voyages limit the number of passengers. In 2018–19, only 98 passengers (excluding crew and expedition staff) visited the Ross Sea, whereas some 514 passengers visited the region in 2019–20 (IAATO 2021), when 99% of tourists departed from South American ports (Carey 2020).

During this period, a tourist vessel visited Commonwealth Bay in the Australian Antarctic Territory in January 2018 for the first time in 7 years. A large iceberg, B90B, had blocked the entrance to the bay for several years.

Tourists travel during the Antarctic summer, the breeding season for most Antarctic wildlife. Environmental aspects of tourism are regulated through the Protocol on Environmental Protection to the Antarctic Treaty, implemented by each treaty party, as is the case for all activities. Safety and operational aspects of tourism activities will be subject to measures agreed by the Antarctic Treaty parties, although the entry into force of the relevant measures is lagging. In addition, the industry develops and implements self-regulatory practices. There are calls for additional regulations through the Antarctic Treaty Consultative Meeting because of increasing numbers of visitors and vessels travelling to the continent, as well as the increasing variety of adventure activities offered by tour operators (Walton 2018, Carey 2020). Potential impacts of human activities on Antarctic values include disturbance to wildlife, pollution (chemical, noise and light), and introduction of non-native organisms.

In 2020, 43 tour operators active in Antarctica were nationals of signatory nations of the Antarctic Treaty, meaning that commercial tourism is almost universally carried out within the framework of the treaty system. Companies are keen to increase their markets, and build new ships to replace old ones and to add to the current fleet. Some 70 vessels were projected to operate by 2021 (Walton 2018); the COVID-19 crisis dampened these ambitions.

The impact of tourism is considered through the environmental impact assessments required for all activities under the Protocol, although on-site monitoring and verification of impacts is limited. General and site-specific visitor guidelines assist tourism operators to carry out their activities in an appropriate manner, including keeping safe distances between people and wildlife. However, long-term and additive impacts have not been examined in detail, nor has there been a fine-scale assessment of effects on plants and soil organisms (Carey 2020). For example, trampling can change soil properties, decrease the habitat quality of soil organisms and affect soil respiration (Tejedo et al. 2014). Tourism operations have expanded significantly in the past 2 decades, and activities are becoming more diversified (e.g. more adventure activities, more fly–cruise operations) (Liggett et al. 2017).

Macquarie Island is managed by Tasmania's Parks and Wildlife Service. Commercial tour operators must apply to the service for permission to visit the island. Quotas limit access to 18 vessels with up to 1,500 tourists per financial year (Tasmania Parks and Wildlife Service 2020). In the 5 years from 2015–16 to 2019–20, an average of 7 tourist vessels and 586 passengers per year visited the island (N Carmichael, Tasmanian Parks and Wildlife Service, pers. comm., 22 July 2021).

Bioprospecting

Bioprospecting is the systematic search for biological products (biochemical or genetic) from plants, animals and microbes that can be developed commercially for use in food products, bioremediation, agriculture, pharmaceuticals, cosmetics and so on (O'Connor 2016, Kumar et al. 2018). Globally, companies spend significant sums on finding and commercialising compounds derived from biological resources, attracting significant profits. For example, sales of drugs derived from the English yew (*Taxus baccata*) generated US$2.3 billion in 2000 (Beattie et al. 2005).

Bioprospecting activities have been taking place in Antarctica since at least 1995, mainly focused on the marine environment (Hemmings & Rogan-Finnemore 2008). Recently, bioactive compounds with potential commercial uses were isolated from fungi in glacial ice (de Menezes et al. 2020), lakes (Ogaki et al. 2020a) and deep-sea sediments (Ogaki et al. 2020b). Antarctic yeasts produce enzymes with potential use in industries, such as the food, wine, and textile industries (Martorell et al. 2019).

The pharmaceutical industry already uses various genetic materials sourced from Antarctica, such as the hydrolase enzyme from Antarctic krill, which prevents immune rejection reactions; melanin derived from the Antarctic black yeast *Nadsoniella nigra*, which has cytotoxic activity in human cancer cells (Guyomard 2010); and a bacterial glycoprotein that assists wound healing. A protein from Antarctic krill improves dye uptake in cotton fabrics (Pisitsak et al. 2018), and there are many more examples (Lohan & Johnston 2003).

Considerable efforts and resources are required for successful bioprospecting. From finding a compound to achieving a marketable product can take decades and hundreds of millions of dollars. Biological prospecting occurs in the Antarctic region, and a 2020 survey conducted by the Scientific Committee on Antarctic Research summarised bioprospecting or natural products research undertaken by countries active in Antarctica, and related patents. The Antarctic Treaty Consultative Meeting has agreed that the Antarctic Treaty System is the appropriate international framework for managing the collection of biological material in the Antarctic Treaty area and for considering its use. Bioprospecting activities in the Antarctic Treaty area are subject to the provisions of the Antarctic Treaty and its Environmental Protocol, including the requirement for prior environmental impact assessment. Harvesting of marine organisms would also be subject to the CCAMLR.

Non-native species

Non-native and invasive species can threaten Antarctic species. This threat is likely to increase with climate change, and with increasing speed and volume of travel to Antarctica by tourists and national programs. Recent risk assessments have identified 14 invasive species at highest risk of establishing in the most rapidly changing and highest-traffic areas on the Antarctic Peninsula, comprising 9 marine invertebrates, 2 terrestrial invertebrates, a kelp and 2 terrestrial flowering plants (Hughes et al. 2020).

In 2011, the Committee for Environmental Protection adopted the *Non-native species manual*, which provides guidelines to help parties prevent or minimise the introduction of non-native species to Antarctica. The manual makes recommendations about the transfer of species into the Antarctic terrestrial and marine environments, as well as between sites in Antarctica (CEP 2011).

Terrestrial species

The Antarctic and subantarctic environments are fragile and vulnerable. Australia has obligations under the Antarctic Treaty System, and national and state legislation to protect the environment. This includes robust biosecurity measures to reduce the risk of introducing non-native species to the environment.

The introduction of non-native, sometimes invasive, species has significantly altered the landscape, the composition of ecosystems and species interactions on many subantarctic islands (Frenot et al. 2005). Various factors increase the potential for non-native species to establish in the terrestrial environment. These include glacier retreat, an increase in ambient temperatures, and precipitation falling as rain rather than snow. These changes are furthering the establishment of non-native plants and microbes. Human activities can also introduce seeds and microbes, particularly at or near research stations and during field activities.

At Macquarie Island, 5 non-native vascular plants have become established since the island's discovery. Two of these species were successfully eradicated, but the remaining 3 are still thriving. The 2 main non-native invasive plant species are the annual meadow grass *Poa annua,* a small grass that can outcompete some native species, and the perennial chickweed *Cerastium fontanum* (March-Salas & Pertierra 2020). Disturbed sites, such as walking tracks, are particularly suited to colonisation by annual meadow grass. Research is currently underway to evaluate its distribution and impact to find ways to eradicate this invasive species in the near future (Williams et al. 2013).

Throughout the subantarctic, many Eurasian weeds have established. Many of those originate from alpine or boreal environments and are thus already cold adapted. The effects of climate change, including increases in temperatures, and changes in precipitation and wind conditions, may allow more non-native plant species to survive and reproduce, while native species may not be able to adapt to the new conditions (March-Salas & Pertierra 2020).

On Macquarie Island, there are also 28 introduced invertebrate species. The presence of some introduced invertebrates may have a negative impact on the richness and density of native invertebrate species (Terauds et al. 2011). Non-native invertebrates include 2 terrestrial crustaceans (an isopod – *Styloniscus otakensis*, and an amphipod – *Puhuruhuru patersoni*) (Greenslade et al. 2008), 2 species of predatory flat worms (*Kontikia andersoni* and *Arthurdendyus vegrandis*) (Greenslade et al. 2007) and two species of springtails (*Protaphorura fimata* and *Proisotoma minuta*) (Phillips et al. 2017). When and how these organisms were introduced to the island are difficult to establish. Should their distribution spread across the island, it might be difficult to eliminate them. Non-native predatory species may have particularly damaging impacts on native populations.

There is also a risk of invertebrates being transported unintentionally to Antarctica. Beetles (Coleoptera), flies (Diptera) and butterflies (Lepidoptera) often enter large cargo containers. Many insects are still alive when they reach Antarctica (Houghton et al. 2016). For example, at Casey Station, a small fly (*Lycoriella ingenua*) was first recorded in the wastewater treatment plant and subfloor spaces in 1998, and proved very difficult to eradicate. Recent eradication efforts appear to have been successful, but monitoring is continuing (COMNAP 2019).

Introduced vertebrates can also have a devastating impact on native species. On various subantarctic islands, house mice (*Mus musculus*) caused widespread decreases in the breeding success of several seabird species by taking eggs and attacking live chicks (Dilley et al. 2017). There is evidence that mice attack adult seabirds, such as northern giant petrels (*Macronectes halli*) and albatrosses (Jones et al. 2019). Since a successful eradication program at Macquarie Island in 2010–11, the island has remained free of mice (Springer 2018).

Marine species

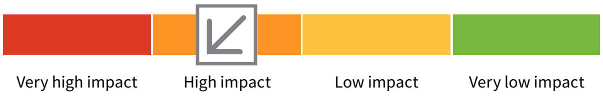
Non-native marine species can find their way into Antarctic waters via different pathways. Microorganisms, plants and animals may be transported on the hull of ships (fouling) or in ballast water (Lewis et al. 2003). Although many ship hulls are painted with antifouling paint, the constant abrasion of the hull of Antarctic vessels travelling through sea ice diminishes the paint's effectiveness. Ships with long layover periods outside the Antarctic shipping season are particularly at risk of carrying non-native species into subantarctic or Antarctic waters (Lewis et al. 2003).

Although ballast water tends to be taken up rather than discharged in Antarctic waters (e.g. after vessels have resupplied a station), the Antarctic Treaty nations agreed to a set of guidelines for the exchange of ballast water in the treaty area (Secretariat of the Antarctic Treaty 2006). These include recommendations for ships to have a Ballast Water Management Plan and a record of ballast water operations.

For many years, exchange of ballast water appeared to be the main transport mechanism for marine non-native species. However, rafts of non-Antarctic kelp carry a vast array of organisms and can drift across very long distances into Antarctic waters (Fraser et al. 2018). In the past, these organisms may not have survived in the frigid waters of the Southern Ocean, but, as sea temperatures increase, so does the likelihood that potentially invasive species may reach Antarctica and establish there (Avila et al. 2020). The first settlement of a mussel (*Mytilus* cf. *platensis*) was reported from the South Shetland Islands, West Antarctica, in 2019 (Cárdenas et al. 2020).

Assessment Pressures on the Antarctic environment

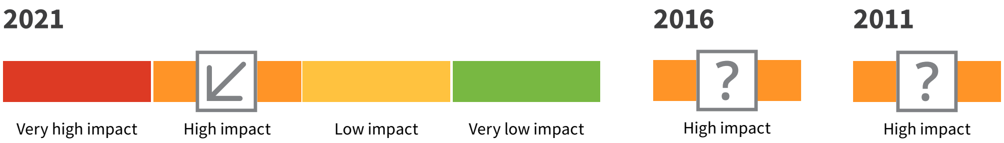
2021



Adequate confidence

The impacts of climate change and pollution on the Antarctic environment are high and increasing.

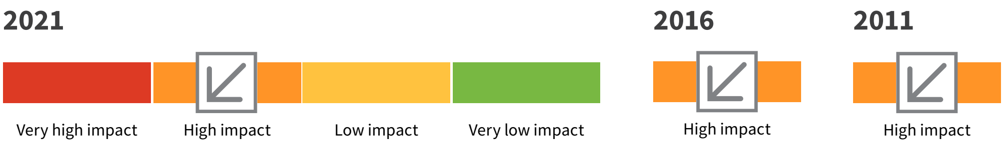
Assessment Climate change



Adequate confidence

Climate change is ongoing and increasingly affects Antarctic ecosystems.

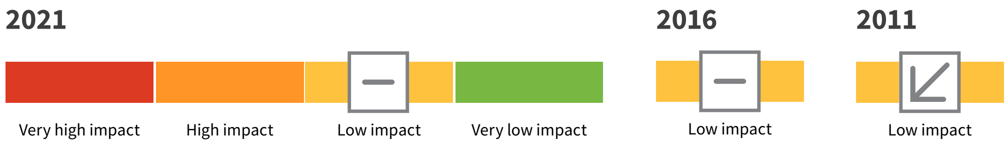
Assessment Marine pollution



Adequate confidence

Marine pollution is a global challenge; although Antarctica is still less affected than other regions, micro- and nano-plastics have been detected in the food web.

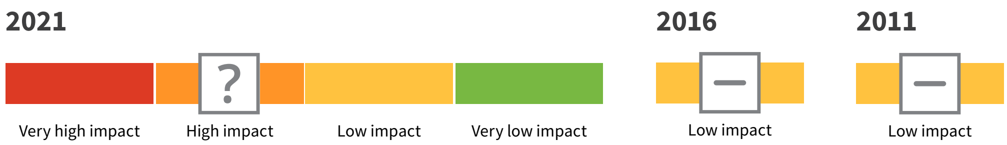
Assessment Commercial fisheries



Adequate confidence

All commercial fisheries in the Southern Ocean are managed by the Commission on the Conservation of Antarctic Marine Living Resources, which applies an ecosystem-based management approach. Exploratory fisheries for toothfish operate in East Antarctica.

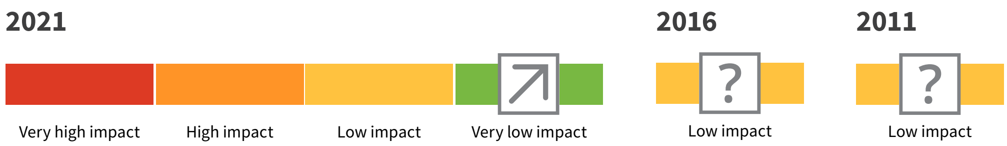
Assessment Tourism



Adequate confidence

Impacts of tourism vary with the site visited. Some sites receive many more visitors than others.

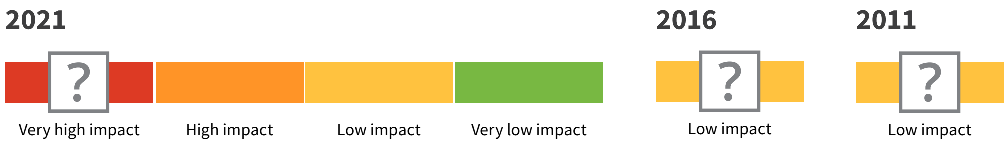
Assessment Non-native species – animals



Adequate confidence

Eradication of non-native introductions (e.g. rabbits and rodents on Macquarie Island) has been successful.

Assessment Non-native species – plants



Very limited confidence

Invasive plants may be spreading.

Assessment ratings

For assessments in the 'Pressures' section

- **Very low impact:** Pressures do not degrade or only negligibly degrade the state of the environment.
- **Low impact:** Pressures minimally degrade the state of the environment over a small extent and/or with low severity.
- **High impact:** Pressures moderately degrade the state of the environment over a moderate extent and/or with moderate severity.
- **Very high impact:** Pressures strongly degrade the state of the environment over a large extent and with a high degree of severity.

Trend

- **Improving:** The situation has improved since the previous assessment (2016 state of the environment report).
- **Stable:** The situation has been stable since the previous assessment.
- **Deteriorating:** The situation has deteriorated since the previous assessment.
- ? **Unclear:** It is unclear how the situation has changed since the previous assessment.

Management

National and international frameworks

A suite of international agreements, collectively known as the Antarctic Treaty System, governs Antarctica, and is designed to take into account the characteristics and environmental challenges of the Antarctic region. These agreements establish Antarctica as a natural reserve devoted to peace and science. Environmental protection and conservation of marine living resources are key objectives. Parties to these agreements fulfil their obligations through national legislation and supporting administrative arrangements, and environmental management arrangements for activities in Antarctica conducted by their nationals. Under the Environmental Protocol to the treaty, environmental impact assessments are required for all human activities in Antarctica, including tourism.

The Australian Government's 2016 Australian Antarctic Strategy and 20 Year Action Plan (Australian Antarctic Programme 2016) identifies that one of Australia's key national interests in Antarctica is to protect the Antarctic environment. Australia promotes best practice in environmental stewardship across all aspects of the Australian Antarctic Program. Australia implements and manages practical ways to minimise the effects of activities in Antarctica, and addresses past impacts by cleaning up former work and waste disposal sites.

Australia works in close collaboration with other nations active in the region, and plays a leading role in international forums, such as the Antarctic Treaty Consultative Meeting, its Committee for Environmental Protection, the Commission for the Conservation of Antarctic Marine Living Resources, and the Agreement on the Conservation of Albatrosses and Petrels.

Australia also plays a significant role in the Southern Ocean in combating illegal, unreported and unregulated fishing, and in conserving albatross and petrel species across their extensive range in these higher latitudes. Australia conducts and supports science to inform the responsible management and protection of Antarctica.

Australian legislation and guidance

Australia's international obligations arising from the agreements of the Antarctic Treaty System come into effect through domestic law. The primary pieces of Australian legislation are:

- *Antarctic Treaty (Environment Protection) Act 1980* – gives effect to the 1991 Protocol on Environmental Protection to the Antarctic Treaty, which includes environmental protection principles, including biosecurity, and requirements for all activities in the Antarctic Treaty area
- *Antarctic Marine Living Resources Conservation Act 1981* – implements the requirements arising from the Convention on the Conservation of Antarctic Marine Living Resources.

Subantarctic islands

Australia's subantarctic islands are located outside the Antarctic Treaty area. The Australian Antarctic Division (AAD) manages the Territory of Heard Island and McDonald Islands, and the Heard Island and McDonald Islands Marine Reserve on behalf of the Australian Government. Macquarie Island and nearby islets are part of the state of Tasmania and are managed by the Tasmanian Department of Primary Industries, Parks, Water and Environment.

The *Heard Island and McDonald Islands Act 1953* provides a legal regime for Heard Island and McDonald Islands. Under this 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 World Heritage site, located within a Commonwealth Reserve proclaimed under and protected by the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). All activities in the territory must be undertaken in accordance with the *Heard Island and McDonald Islands Marine Reserve management plan 2014–24* (Australian Antarctic Division 2014).

Macquarie Island is also a World Heritage site. The Tasmanian Government manages the Macquarie Island Commonwealth Marine Reserve adjacent to the Macquarie Island Nature Reserve. The marine reserve is subject to the EPBC Act, and activities in the reserve are governed by the *South-east Commonwealth Marine Reserves Network management plan 2013–23* (Australian Government Director of National Parks 2013).

All albatross and petrel species listed under the Agreement on the Conservation of Albatrosses and Petrels (ACAP) that are native to Australia, including the endemic shy albatross, are listed migratory species under the EPBC Act. The listed threatened species of albatrosses and petrels under the legislation are subject to a national recovery plan. The draft of the third *National recovery plan for albatrosses and petrels* (2021) was open for public comment until 27 August 2021, and is currently being evaluated (DAWE 2021a). When adopted, it will replace the plan adopted in 2011.

Station management and training

As lead agency for Australia's Antarctic program, the AAD ensures that everyone involved in the program is aware of their personal responsibilities to care for the environment. When appointed, all expeditioners must agree to abide by a code of personal behaviour that emphasises a commitment to Australia's environmental management responsibilities. Induction and training of new employees includes an introduction to relevant Australian laws and the AAD's approach to environmental issues.

At Australia's Antarctic and subantarctic stations, the station leader is responsible on the ground for environmental management, including implementation of policies, standard operating procedures and management decisions from AAD; the station environment committee, a station environmental officer and a station waste-management officer assist the station leader in this task. However, everybody is responsible for environmental protection. A web-based reporting system allows expedition members to submit information or suggestions on environmental issues.

Recently, the AAD identified and implemented improvements to the biosecurity system, such as improved cargo biosecurity procedures, checklists, training and supplier declarations. The Environmental Management System enables continued improvement of biosecurity, and supports ongoing monitoring and reporting (Australian Antarctic Program 2019).

Protected areas

Under the Environmental Protocol to the Antarctic Treaty, all of Antarctica has a high level of environmental protection. However, certain areas receive a higher level of protection if they contain outstanding environmental, scientific, historical, aesthetic or wilderness values (or any combination thereof).

Antarctic Specially Protected Areas

Certain areas are designated as Antarctic Specially Protected Areas (ASPAs) to protect values of outstanding significance. Entry to an ASPA requires a permit issued by a relevant national competent authority, and activities must be conducted in accordance with a management plan that has been agreed by the Committee for Environmental Protection and the Antarctic Treaty Consultative Meeting. Australia has lead management responsibility for 10 ASPAs in East Antarctica, and jointly manages 2 ASPAs with other nations.

Protected areas are one important means of achieving the objectives of the Environmental Protocol to the Antarctic Treaty. Although the Environmental Protocol provides a high level of protection for all of Antarctica, the Antarctic Treaty parties are pursuing efforts to further develop the network of ASPAs, because of increasing pressures from climate change and intensifying human activities. Based on a systematic approach, expanding the network would ensure that it is representative of the continent's biodiversity and other values. At the same time, effective management systems with set conservation objectives are important to increase the resilience of the ASPA network (Coetzee et al. 2017).

Marine protected areas

The Southern Ocean region is unique in its biodiversity. Marine protected areas (MPAs) are widely considered an important tool for the management of the great southern region and its conservation. All activities, including use of resources in the Southern Ocean, have been managed effectively under the Antarctic Treaty System.

From the beginning, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) recognised the importance of ecosystem-based management and the precautionary principle. CCAMLR was the first international organisation to endorse the recommendations by the United Nations World Summit in 2002 to develop a network of comprehensive and representative MPAs in the Southern Ocean (CCAMLR 2011). CCAMLR 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. MPAs are part of this approach. In 2011, CCAMLR adopted Conservation Measure 91-04, which sets out the 'General framework for the establishment of CCAMLR marine protected areas'. Major goals are the establishment of a network of MPAs representative of biodiversity, habitats and marine ecosystems; and the protection of key ecosystem processes and critical features to maintain ecosystem resilience or enable adaptation to climate change (CCAMLR 2011).

Although the aim to have a representative network of MPAs in place by 2012 was not achieved, 2 MPAs have been established. The first, set up in 2009, was the South Orkney Islands Southern Shelf Marine Protected Area, the first MPA declared in international waters. In CCAMLR Subarea 48.2, an area of around 94,000 square kilometres (km^2) is now protected, which includes important foraging areas for penguins, a range of flying seabirds and marine mammals, as well as a species-rich benthic region (Trathan & Grant 2020). In 2016, CCAMLR members reached consensus on declaring a second MPA in the Ross Sea region (CCAMLR 2016) that is currently the world's largest MPA, covering 1.55 million km^2 (MFAT n.d.).

Southern Ocean MPAs also exist in national waters around Heard Island and McDonald Islands (Australia), the Kerguelen Islands and the Crozet Islands (France), and the Prince Edward Islands (South Africa).

Currently, 3 further MPAs have been proposed and are still being negotiated: the Weddell Sea MPA, which would cover 4.2 million km^2 (Teschke et al. 2021); an MPA in East Antarctica comprising 3 areas collectively covering about 1 million km^2; and an MPA in the region of the western Antarctic Peninsula (Hogg et al. 2020).

Convention on the Conservation of Antarctic Marine Living Resources

The conservation of Antarctic marine living resources is subject to the regulations imposed under the CCAMLR. This convention came into force in 1982 as part of the Antarctic Treaty System. CCAMLR comprises 25 member states and the European Union. A further 10 countries have agreed to the terms of the convention. Article I 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' (UN 1980). The commission manages about 10% of the world's oceans (Brooks 2013).

Antarctic Treaty parties established the convention because of a growing concern that an increase in krill catches in the Southern Ocean could have a serious effect on populations of krill and other marine life, particularly birds, seals and fish, all of which depend on krill for food (see Krill fishing).

The objective of the convention is the conservation of Antarctic marine living resources. CCAMLR has applied an ecosystem-based management system to ensure that fisheries are sustainable, and that the needs of dependent predators and ecosystems are considered. CCAMLR was the first international convention applying the ecosystem-based approach to its fisheries management strategy (Arnaudo 2005). This sets CCAMLR apart from regional fishery management organisations, which largely focus on the management and production of harvested species and often deal with single species only.

CCAMLR considers the needs of krill-dependent predators and sets conservative catch limits to safeguard their requirements. Since several krill-dependent predators act as indicators of the health of the Southern Ocean ecosystem, CCAMLR developed the Ecosystem Monitoring Program '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' (CCAMLR 1984). As part of the precautionary approach, CCAMLR establishes conservation and management measures to maintain populations of harvested species at levels that ensure stable recruitment.

CCAMLR continues to work on achieving consensus among party members to achieve its objectives to protect the Antarctic environment, habitats, species and ecological processes, and increase resilience to climate change (CCAMLR 2011). CCAMLR also encourages national programs operating in Antarctica to undertake targeted fisheries-related research to ensure that there is constant recruitment into populations of target species, but also provide for the needs of dependent species (Constable 2002).

Agreement on the Conservation of Albatrosses and Petrels

The Agreement on the Conservation of Albatrosses and Petrels (ACAP) aims to achieve and maintain a favourable conservation status for albatrosses and petrels. This agreement came into force in 2004, as part of the framework of international agreements under the auspices of the Convention on the Conservation of Migratory Species of Wild Animals. ACAP applies to the species listed in Annex 1 to the agreement: currently all 22 of the world's albatross species and 9 petrel species (ACAP 2020b).

ACAP has 13 member states, including Australia. The agreement enhances cooperation and builds capacity among its member states, and works closely with regional fisheries and conservation bodies (ACAP 2021a).

Australia and other concerned nations established the agreement because of a growing concern about rapid decreases in global albatross and petrel populations. These decreases were due to threats at sea, mainly associated with interactions with fishing gear, and threats on land affecting breeding sites, including human disturbance, predation and habitat damage by invasive species.

ACAP applies the precautionary approach when developing measures to enhance the conservation status of these species. ACAP promotes best and improving practices in seabird bycatch mitigation in fisheries, and provides guidelines for addressing threats affecting albatross and petrel breeding sites. It advocates the implementation of effective technologies and techniques to avoid or minimise the incidental catch of seabirds during fishing operations. It also promotes the monitoring of the degree and extent of seabird mortalities in global fisheries (ACAP 2021b).

ACAP has established World Albatross Day, celebrated on 19 June each year (the date when the agreement opened for signature in 2001). This initiative helps to raise public awareness and understanding about albatross conservation. Each year, ACAP selects a theme to give particular attention to a conservation concern that affects albatrosses. In 2021, the theme for World Albatross Day is 'Ensuring albatross-friendly fisheries'. It will highlight some of the successful initiatives taken in coastal state and high-seas fisheries to reduce albatross bycatch (ACAP 2020a).

International Whaling Commission

In the 20th century, commercial whaling operations killed more than 2 million whales in the Southern Hemisphere, mostly in the Southern Ocean. Many populations were reduced to about 1% of their previous size (Clapham & Scott Baker 2018). Following the recognition that many populations of large whales were near to extinction, the International Convention for the Regulation of Whaling (ICRW) and its regulatory body, the International Whaling Commission (IWC), were established to regulate whaling activities in 1946. However, most whale populations continued to decline for the next few decades.

Finally, in 1986, the IWC set all commercial catch limits to zero, and established the 'moratorium' on commercial whaling that is still in place today. In 1994, the IWC created the Southern Ocean Whale Sanctuary (SOWS), which excludes all commercial whaling from an area of about 50 million km^2. However, the moratorium on commercial whaling and the SOWS do not prohibit whaling under Article VIII of the ICRW.

Since 1946, the IWC has grown from 15 to 88 member governments. It continues to manage whaling activities but increasingly works to address other human impacts on whale and dolphin populations, such as fisheries bycatch, entanglement, noise and pollution.

Data and monitoring

Data and monitoring are essential to understanding interactions in the Antarctic region, particularly the large-scale, long-term changes and impacts due to climate change.

The Australian Antarctic Division (AAD) leads Australia's scientific program in Antarctica, which is undertaken on behalf of the Australian Government by Australian and international researchers. The research program covers physical and life sciences in the atmospheric, terrestrial and marine domains, as well as human biology and medical research. It also includes long-term observational activities, such as a network of meteorological facilities; space weather monitoring; seismic, magnetic and geodetic networks; and hydrographic and bathymetric mapping.

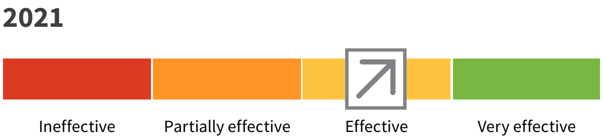
The key areas of research include:

- environmental protection and management – research and monitoring to improve management of Antarctica and the Southern Ocean, including climate change impacts, fisheries management and environmental remediation
- ice, ocean, atmosphere and Earth systems – understanding the impact of Antarctica and the Southern Ocean on Australia and the world, including high-latitude climate science, interpretation of past climate records to inform climate understanding, geophysical mapping, and atmosphere and weather studies
- human presence and activities in Antarctica – including polar medicine and human biology, space and astronomy, social sciences (policy and law), and pollution monitoring.

The Australian Antarctic Strategic Plan, developed by the Australian Antarctic Science Council in 2019, directs research activities. The plan delivers key research outcomes outlined in the Australian Antarctic Strategy and 20 Year Action Plan.

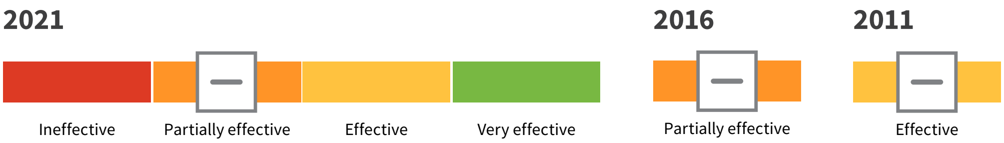
Although the AAD leads Australia's scientific program in Australia, other key government initiatives are also contributing to long-term sustained observations of the Southern Ocean – in particular, the Integrated Marine Observing System (IMOS 2021).

Assessment Effectiveness of Antarctic management



Management of the Australian Antarctic Territory and protected areas is generally effective in protecting environmental values.

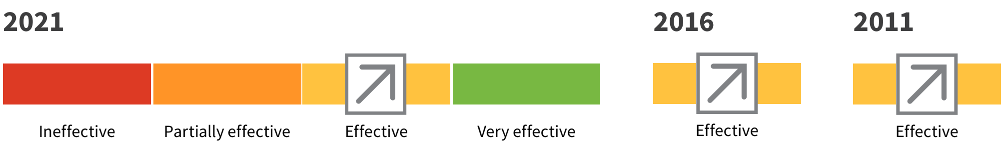
Assessment World Heritage of subantarctic islands and protected areas under the Antarctic Treaty



Adequate confidence

Management plans are in place and are reviewed regularly. Natural and cultural heritage values are being preserved.

Assessment Land use and management



Adequate confidence

Australia's Antarctic environmental management policy for the Australian Antarctic Territory and its external territories in the subantarctic is consistent with Australia's obligations under the Antarctic Treaty.

Assessment ratings

For assessments in the 'Management' section

- **Very effective:** Management measures maintain or improve the state of environment and secure it against known pressures.
- **Effective:** Management measures maintain or improve the state of the environment, but pressures remain as significant factors that degrade environment values.
- **Partially effective:** Management measures have limited impact on maintaining or improving the state of the environment.
- **Ineffective:** Management measures are failing to stop substantial declines in the state of the environment.

Trend

- **Improving:** The situation has improved since the previous assessment (2016 state of the environment report).
- **Stable:** The situation has been stable since the previous assessment.
- **Deteriorating:** The situation has deteriorated since the previous assessment.
- **Unclear:** It is unclear how the situation has changed since the previous assessment.

Authors and acknowledgements

Authors

Barbara Wienecke

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Approach

Generally, limited data are available to assess many aspects of the Antarctic environment. This is largely a consequence of the remoteness and sparse habitation of the region. Specific information is available to assess trends and changes in the physical environment. This includes palaeoclimate records from ice cores that extend back hundreds of thousands of years, synoptic weather observations generally starting in the 1950s, and satellite remote-sensing data from the late 1970s onwards. For the various components of the ecosystem, far sparser records are available. For many species, such as baleen whales, accurate population assessments remain unavailable.

This report presents our best available assessments of the state and trends of the Antarctic environment (the area south of 60°S, the Southern Ocean and Australia's subantarctic islands), primarily as they relate to Australia's interests in the region. Overall, the material presented here is largely an update on the 2016 state of the environment report, primarily informed by the peer-reviewed literature that has appeared in the intervening 5 years. Consequently, almost all the assessments presented here are directly comparable to those presented in 2016. For the physical environment, many aspects of change are occurring on multiyear or longer timescales because of the nature of physical processes associated with the Antarctic atmosphere, ice sheet and surrounding oceans. Thus, the assessed changes and trends are generally identical to those presented in the 2016 state of the environment report.

The 2016 state of the environment report was prepared using the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013) which provided a comprehensive picture of the state of the Antarctic environment at its release in 2013. In preparing the present report, we have primarily used observational assessments from subsequent major reports including the *IPCC special report on the ocean and cryosphere in a changing climate* (IPCC in press-a), the *Scientific assessment of ozone depletion: 2018* (WMO 2018) and the Sixth Assessment Report of the IPCC (IPCC 2021). In addition to other peer-reviewed literature, we have also used the opinion of experts in specific fields and, where possible, we have made use of a variety of up-to-date environmental and management data collected in support of the Australian Antarctic Program.

In general, our assessment of the confidence rating for grade and trend is graded using the 3 levels used for the 2016 state of the environment report ('adequate', 'limited' and 'low'). At present, a finer assessment using the 2 additional grades adopted in this report ('somewhat adequate' and 'very limited') cannot be applied confidently for most of the Antarctic topics considered here.

References

Abernathey RP, Cerovecki I, Holland PR, Newsom E, Mazloff M & Talley LD (2016). Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geoscience* 9(8):596–601.

Abram NJ, Henley BJ, Sen Gupta A, Lippmann TJR, Clarke H, Dowdy AJ et al. (2021). Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth and Environment* 2(1):8.

ACAP (Agreement on the Conservation of Albatrosses and Petrels) (2020a). Introduction to World Albatross Day, ACAP, Hobart, https://www.acap.aq/world-albatross-day/introduction-to-world-albatross-day.

ACAP (Agreement on the Conservation of Albatrosses and Petrels) (2020b). *Albatross and petrel species to which the agreement applies*, ACAP, Hobart.

ACAP (Agreement on the Conservation of Albatrosses and Petrels) (2021a). *Agreement on the conservation of albatrosses and petrels*, ACAP, Hobart, accessed 10 May 2021, https://www.acap.aq/.

ACAP (Agreement on the Conservation of Albatrosses and Petrels) (2021b). ACAP instruments, ACAP, Hobart, https://www.acap.aq/agreement-text.

ACE CRC (Antarctic Climate and Ecosystems Cooperative Research Centre) (2010). *ACE CRC report card: Southern Ocean acidification*, RC01-101123, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart.

AFMA (Australian Fisheries Management Authority) (2015). Mackerel icefish, AFMA, Canberra, accessed 5 Sep 2021, https://www.afma.gov.au/fisheries-management/species/mackerel-icefish.

Ainley D, Woehler EJ & Lescroël A (2017). Birds and Antarctic sea ice. In: Thomas DN (ed), *Sea ice*, 3rd edn, John Wiley & Sons, Hoboken, New Jersey, 570–582.

Ainley DG, LaRue MA, Stirling I, Stammerjohn S & Siniff DB (2015). An apparent population decrease, or change in distribution, of Weddell seals along the Victoria Land coast. *Marine Mammal Science* 31(4):1338–1361.

Ainley DG, Cziko PA, Nur N, Rotella JJ, Eastman JT, Larue M, Stirling I & Abrams PA (2021). Further evidence that Antarctic toothfish are important to Weddell seals. *Antarctic Science* 33(1):17–29.

Amesbury MJ, Roland TP, Royles J, Hodgson DA, Convey P, Griffiths H & Charman DJ (2017). Widespread biological response to rapid warming on the Antarctic Peninsula. *Current Biology* 27(11):1616–1622.e2.

Amos M, Young PJ, Hosking JS, Lamarque JF, Abraham NL, Akiyoshi H et al. (2020). Projecting ozone hole recovery using an ensemble of chemistry–climate models weighted by model performance and independence. *Atmospheric Chemisty and Physics* 20(16):9961–9977.

Andriuzzi WS, Adams BJ, Barrett JE, Viriginia RA & Wall DH (2018). Observed trends of soil fauna in the Antarctic Dry Valleys: early signs of shifts predicted under climate change. *Ecology* 99(2):312–321.

Antarctic Treaty Secretariat (nd). Antarctic Protected Areas database, Antarctic Treaty Secretariat, Buenos Aires, 20 October, https://www.ats.aq/devph/en/apa-database.

Aoki S, Yamazaki K, Hirano D, Katsumata K, Shimada K, Kitade Y, Sasaki H & Murase H (2020). Reversal of freshening trend of Antarctic bottom water in the Australian-Antarctic Basin during 2010s. *Scientific Reports* 10:14415.

Arblaster JM, Meehl GA & Karoly DJ (2011). Future climate change in the Southern Hemisphere: competing effects of ozone and greenhouse gases. *Geophysical Research Letters* 38(2):L02701.

Arcalís-Planas A, Sveegaard S, Karlsson O, Harding KC, Wåhlin A, Harkonen T & Teilmann J (2015). Limited use of sea ice by the Ross seal (*Ommatophoca rossii*), in Amundsen Sea, Antarctica, using telemetry and remote sensing data. *Polar Biology* 38(4):445–461.

Arenz BE, Blanchette RA & Farrell RL (2014). Fungal diversity in Antarctic soils. In: Cowan DA (ed), *Antarctic terrestrial microbiology: physical and biological properties of Antarctic soils*, Springer-Verlag, Berlin, 35–53.

Armour KC & Bitz CM (2015). Observed and projected trends in Antarctic sea ice. *US CLIVAR Variations* 13(4):12–19.

Armour KC, Marshall J, Scott JR, Donohoe A & Newsom ER (2016). Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nature Geoscience* 9(7):549–554.

Arnaudo R (2005). A short history of CCAMLR: a unique conservation and management regime. In: *Proceedings of the CCAMLR Symposium*, Valdivia, Chile, 5–8 April 2005, Commission for the Conservation of Antarctic Marine Resources, Hobart.

Arrigo KR, van Dijken GL, Alderkamp AC, Erickson ZK, Lewis KM, Lowry KE, Joy-Warren HL, Middag R, Nash-Arrigo JE, Selz V & van de Poll W (2017). Early spring phytoplankton dynamics in the western Antarctic Peninsula. *Journal of Geophysical Research: Oceans* 122(12):9350–9369.

Atkinson A, Siegel V, Pakhomov EA, Jessopp MJ & Loeb V (2009). A re-appraisal of the total biomass and annual production of Antarctic krill. *Deep Sea Research Part I: Oceanographic Research Papers* 56(5):727–740.

Atkinson A, Hill SL, Pakhomov EA, Siegel V, Reiss CS, Loeb VJ, Steinberg DK, Schmidt K, Tarling GA, Gerrish L & Sailley SF (2019). Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. *Nature Climate Change* 9(2):142–147.

ATS (Antarctic Treaty Secretariat) (2021). Resolution 5 (2019) – ATCM XLII – CEP XXII, Prague, ATS, Buenos Aires, accessed 27 May 2021, https://www.ats.aq/devAS/Meetings/Measure/705.

Australian Antarctic Division (2014). *Heard Island and McDonald Islands Marine Reserve management plan 2014–2024*, Australian Government Department of the Environment, Canberra.

Australian Antarctic Program (2019). Environmental management system, Australian Government Department of Agriculture, Water and the Environment, Australian Antarctic Division, Kingston, Tasmania, accessed 27 May 2021, https://www.antarctica.gov.au/about-antarctica/environment/environment-policy-and-management/environmental-management-system/.

Australian Antarctic Program (2021). Shipping and flight schedules, Australian Government Department of Agriculture, Water and the Environment, Australian Antarctic Division, Kingston, Tasmania, accessed 15 Oct 2020, https://www.antarctica.gov.au//antarctic-operations/travel-and-logistics/shipping-and-air-schedules/.

Australian Antarctic Programme (2016). *Australian Antarctic strategy and 20 year action plan*, Australian Government, Canberra.

Australian Government Director of National Parks (2013). *South-east Commonwealth Marine Reserves Network management plan 2013–23*, Director of National Parks, Canberra.

Avila C, Angulo-Preckler C, Martín-Martín RP, Figuerola B, Griffiths HJ & Waller CL (2020). Invasive marine species discovered on non-native kelp rafts in the warmest Antarctic island. *Scientific Reports* 10(1):1639.

Bamber JL, Westaway RM, Marzeion B & Wouters B (2018). The land ice contribution to sea level during the satellite era. *Environmental Research Letters* 13(6):063008.

Ban S, Ohi N, Leong SCY, Takahashi KT, Riser CW & Taguchi S (2007). Effect of solar ultraviolet radiation on survival of krill larvae and copepods in Antarctic Ocean. *Polar Biology* 30(10):1295–1302.

Banerjee A, Fyfe JC, Polvani LM, Waugh D & Chang KL (2020). A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. *Nature* 579(7800):544–548.

Barbraud C & Weimerskirch H (2006). Antarctic birds breed later in response to climate change. *Proceedings of the National Academy of Sciences* 103(16):6248–6251.

Bargagli R (2005). *Ecological Studies*, vol. 175, *Antarctic ecosystems: environmental contamination, climate change, and human impact*, Springer-Verlag, Berlin.

Barnes DKA (2017). Iceberg killing fields limit huge potential for benthic blue carbon in Antarctic shallows. *Global Change Biology* 23(7):2649–2659.

Barnes DKA, Fleming A, Sands CJ, Quartino ML & Deregibus D (2018). Icebergs, sea ice, blue carbon and Antarctic climate feedbacks. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376(2122):20170176.

Bax N, Sands CJ, Gogarty B, Downey RV, Moreau CVE, Moreno B, Held C, Paulsen ML, McGee J, Haward M & Barnes DKA (2021). Perspective: increasing blue carbon around Antarctica is an ecosystem service of considerable societal and economic value worth protecting. *Global Change Biology* 27(1):5–12.

Beattie A, Barthlott W, Kate K, Elisabetsky E, Farrel R, Kheng CT, Prance I, Rosenthal J, Simpson D, Leakey R & Wolfson M (2005). New products and industries from biodiversity. In: Hassan R, Scholes R & Ash N (eds), *Ecosystems and human well-being: current state and trends*, Island Press, Washington, 271–295.

Becker PH, Goutner V, Ryan PG & González-Solís J (2016). Feather mercury concentrations in Southern Ocean seabirds: variation by species, site and time. *Environmental Pollution* 216:253–263.

Beers JM & Jayasundara N (2015). Antarctic notothenioid fish: what are the future consequences of ‘losses’ and ‘gains’ acquired during long-term evolution at cold and stable temperatures? *Journal of Experimental Biology* 218(12):1834–1845.

Bejder M, Johnston DW, Smith J, Friedlaender A & Bejder L (2016). Embracing conservation success of recovering humpback whale populations: evaluating the case for downlisting their conservation status in Australia. *Marine Policy* 66:137–141.

Bereiter B, Eggleston S, Schmitt J, Nehrbass-Ahles C, Stocker TF, Fischer H, Kipfstuhl S & Chappellaz J (2015). Revision of the EPICA dome C CO_2 record from 800 to 600 kyr before present. *Geophysical Research Letters* 42(2):542–549.

Bergstrom DM, Whinam J & Belbin L (2002). A classification of subantarctic Heard Island vegetation. *Arctic, Antarctic, and Alpine Research* 34(2):169–177.

Bergstrom DM, Bricher PK, Raymond B, Terauds A, Doley D, McGeoch MA et al. (2015). Rapid collapse of a sub-Antarctic alpine ecosystem: the role of climate and pathogens. *Journal of Applied Ecology* 52(3):774–783.

Bergstrom DM, Wienecke BC, van den Hoff J, Hughes L, Lindenmayer DB, Ainsworth TD et al. (2021). Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biology* 27(9):1692–1703.

Bernard KS, Gunther LA, Mahaffey SH, Qualls KM, Sugla M, Saenz BT, Cossio AM, Walsh J & Reiss CS (2019). The contribution of ice algae to the winter energy budget of juvenile Antarctic krill in years with contrasting sea ice conditions. *ICES Journal of Marine Science* 76(1):206–216.

Bertinetti S, Ardini F, Vecchio MA, Caiazzo L & Grotti M (2020). Isotopic analysis of snow from dome C indicates changes in the source of atmospheric lead over the last fifty years in East Antarctica. *Chemosphere* 255:126858.

Besseling E, Foekema EM, van Franeker JA, Leopold MF, Kühn S, Bravo Rebolledo EL, Heße E, Mielke L, Kamminga P & Koelmans AA (2015). Microplastic in a macro filter feeder: humpback whale *Megaptera novaeangliae*. *Marine Pollution Bulletin* 95(1):248–252.

Bester MN, Bornemann H & McIntyre T (2017). Antarctic marine mammals and sea ice. In: Thomas DN (ed), *Sea ice*, 3rd edn, John Wiley & Sons, Hoboken, New Jersey, 534–555.

Bhardwaj L, Sharma S, Ranjan A & Jindal T (2019). Persistent organic pollutants in lakes of Broknes Peninsula at Larsemann Hills area, East Antarctica. *Ecotoxicology* 28(5):589–596.

Biersma EM, Jackson JA, Stech M, Griffiths HJ, Linse K & Convey P (2018). Molecular data suggest long-term in situ Antarctic persistence within Antarctica's most speciose plant genus, *Schistidium*. *Frontiers in Ecology and Evolution* 6:77.

Biersma EM, Convey P, Wyber R, Robinson SA, Dowton M, van de Vijver B, Linse K, Griffiths HJ & Jackson JA (2020). Latitudinal biogeographic structuring in the globally distributed moss *Ceratodon purpureus*. *Frontiers in Plant Science* 11:502359.

Bindoff NL & Hobbs WR (2016). Sea-ice-driven shallow overturning. *Nature Geoscience* 9(8):569–570.

Bintanja R, van Oldenborgh GJ, Drijfhout SS, Wouters B & Katsman CA (2013). Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience* 6(5):376–379.

Bintanja R, Severijns C, Haarsma R & Hazeleger W (2014). The future of Antarctica's surface winds simulated by a high-resolution global climate model: 1. Model description and validation. *Journal of Geophysical Research: Atmospheres* 119(12):7136–7159.

Bird JP, Fuller RA & Shaw JDS (2021). Differing ecological responses of seabirds to invasive species eradication. *bioRxiv*:2021.04.07.438878.

BirdLife Australia (2021). Macquarie Island (dataset), BirdLife International, Cambridge, UK, http://datazone.birdlife.org/site/factsheet/macquarie-island-iba-australia.

BirdLife International (2018). Black-browed albatross: *Thalassarche melanophris*. The IUCN red list of threatened species 2018: e.T22698375A132643647, International Union for Conservation of Nature, Cambridge, United Kingdom, accessed 18 Jun 2021, https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22698375A132643647.en.

BirdLife International (2021). Sites & habitats (IBAs and KBAs), BirdLife International, Cambridge, United Kingdom, accessed 27 May 2021, https://www.birdlife.org/worldwide/programmes/sites-habitats-ibas-and-kbas.

Birds Australia (2010). *The state of Australia's birds 2010: islands and birds*, report prepared by Kirkwood J & O'Connor J, Birds Australia, Melbourne.

Bluhm BA, Swadling KM & Gradinger R (2017). Sea ice as a habitat for macrograzers. In: Thomas DN (ed), *Sea ice*, 3rd edn, John Wiley & Sons, Hoboken, New Jersey, 394–414.

Bockheim JG (ed) (2015). *World soils book series*, *The soils of Antarctica*, Springer International Publishing, Basel, Switzerland.

BOM (Bureau of Meteorology) (2019). Temperature and rainfall changes at remote Australian islands and Antarctic sites, BOM, Melbourne, accessed 3 Sep 2021, http://www.bom.gov.au/climate/updates/articles/a033.shtml.

Böning CW, Dispert A, Visbeck M, Rintoul SR & Schwarzkopf FU (2008). The response of the Antarctic circumpolar current to recent climate change. *Nature Geoscience* 1(12):864–869.

Bowman JP, Cavanagh J, Austin JJ & Sanderson K (1996). Novel psychrobacter species from Antarctic ornithogenic soils. *International Journal of Systematic and Evolutionary Microbiology* 46(4):841–848.

Boyd PW (2019). Physiology and iron modulate diverse responses of diatoms to a warming Southern Ocean. *Nature Climate Change* 9(2):148–152.

Bracegirdle TJ, Krinner G, Tonelli M, Haumann FA, Naughten KA, Rackow T, Roach LA & Wainer I (2020). Twenty first century changes in Antarctic and Southern Ocean surface climate in CMIP6. *Atmospheric Science Letters* 21(9):e984.

Bramley-Alves J, Wanek W, French K & Robinson SA (2015). Moss $\delta^{13}C$: an accurate proxy for past water environments in polar regions. *Global Change Biology* 21(6):2454–2464.

Branch TA (2006). *Abundance estimates for Antarctic minke whales from three completed circumpolar sets of surveys, 1978/79 to 2003/04*, International Whaling Commission paper SC/58/IA18, University of Cape Town, South Africa.

Branch TA (2011). Humpback whale abundance south of 60°S from three complete circumpolar sets of surveys. *Journal of Cetacean Research and Management* (3):53–69.

Brandt A, de Broyer C, de Mesel I, Ellingsen KE, Gooday AJ, Hilbig B, Linse K, Thomson MRA & Tyler PA (2006). The biodiversity of the deep Southern Ocean benthos. *Philosophical Transactions of the Royal Society B* 362(1477):39–66.

Brasier MJ, Barnes D, Bax N, Brandt A, Christianson AB, Constable AJ et al. (2021). Responses of Southern Ocean seafloor habitats and communities to global and local drivers of change. *Frontiers in Marine Science* 8:622721.

Bretagnolle V & Gillis H (2010). Predator-prey interactions and climate change. In: Møller AP, Fiedler W & Berthold P (eds), *Effects of climate change on birds*, Oxford University Press, Oxford, United Kingdom, 227–248.

Bricher PK, Lucieer A & Woehler EJ (2008). Population trends of Adélie penguin (*Pygoscelis adeliae*) breeding colonies: a spatial analysis of the effects of snow accumulation and human activities. *Polar Biology* 31(11):1397–1407.

Bridge PD & Spooner BM (2012). Non-lichenized Antarctic fungi: transient visitors or members of a cryptic ecosystem? *Fungal Ecology* 5(4):381–394.

Bromwich DH, Nicolas JP & Monaghan AJ (2011). An assessment of precipitation changes over Antarctica and the Southern Ocean since 1989 in contemporary global reanalyses. *Journal of Climate* 24(16):4189–4209.

Bromwich DH, Nicolas JP, Monaghan AJ, Lazzara MA, Keller LM, Weidner GA & Wilson AB (2013). Central West Antarctica among the most rapidly warming regions on Earth. *Nature Geoscience* 6(2):139–145.

Bronselaer B, Russell JL, Winton M, Williams NL, Key RM, Dunne JP, Feely RA, Johnson KS & Sarmiento JL (2020). Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean. *Nature Geoscience* 13(1):35–42.

Brooks CM (2013). Competing values on the Antarctic high seas: CCAMLR and the challenge of marine-protected areas. *The Polar Journal* 3(2):277–300.

Brooks CM, Ainley DG, Abrams PA, Dayton PK, Hofman RJ, Jacquet J & Siniff DB (2018). Antarctic fisheries: factor climate change into their management. *Nature* 558(7709):177–180.

Brooks ST, Jabour J, van den Hoff J & Bergstrom DM (2019). Our footprint on Antarctica competes with nature for rare ice-free land. *Nature Sustainability* 2(3):185–190.

Burton-Johnson A, Black M, Peter TF & Kaluza-Gilbert J (2016). An automated methodology for differentiating rock from snow, clouds and sea in Antarctica from Landsat 8 imagery: a new rock outcrop map and area estimation for the entire Antarctic continent. *The Cryosphere* 10(4):1665–1677.

Cai S, Hsu PC & Liu F (2021). Changes in polar amplification in response to increasing warming in CMIP6. *Atmospheric and Oceanic Science Letters* 14(3):100043.

Cai W, Santoso A, Wang G, Yeh SW, An SI, Cobb KM et al. (2015). ENSO and greenhouse warming. *Nature Climate Change* 5(9):849–859.

Campbell IB, Claridge GGC & Balks MR (1994). The effect of human activities on moisture content of soils and underlying permafrost from the McMurdo Sound region, Antarctica. *Antarctic Science* 6(3):307–314.

Campbell IB & Claridge GGC (2009). Antarctic permafrost soils. In: Margesin R (ed), *Soil biology,* vol. 16, *Permafrost soils*, Springer, Berlin, Heidelberg, 17–31.

Cannone N, Corinti T, Malfasi F, Gerola P, Vianelli A, Vanetti I, Zaccara S, Convey P & Guglielmin M (2017). Moss survival through in situ cryptobiosis after six centuries of glacier burial. *Scientific Reports* 7:4438.

Cárdenas L, Leclerc JC, Bruning P, Garrido I, Détrée C, Figueroa A, Astorga M, Navarro JM, Johnson LE, Carlton JT & Pardo L (2020). First mussel settlement observed in Antarctica reveals the potential for future invasions. *Scientific Reports* 10:5552.

Carey PW (2020). Is it time for a paradigm shift in how Antarctic tourism is controlled? *Polar Perspectives* (1):Jul.

Carrasco JF, Bozkurt D & Cordero RR (2021). A review of the observed air temperature in the Antarctic Peninsula. Did the warming trend come back after the early 21st hiatus? *Polar Science* 28:100653.

Carroll G, Hedley S, Bannister J, Ensor P & Harcourt R (2014). No evidence for recovery in the population of sperm whale bulls off Western Australia, 30 years post-whaling. *Endangered Species Research* 24(1):33–43.

Carson M, Lyu K, Richter K, Becker M, Domingues CM, Han W & Zanna L (2019). Climate model uncertainty and trend detection in regional sea level projections: a review. *Surveys in Geophysics* 40(6):1631–1653.

Castro MF, Neven JCL, Francelino MR, Schaefer CEGR & Oliveira TS (2021). Seabirds enrich Antarctic soil with trace metals in organic fractions. *Science of the Total Environment* 785:147271.

Cavan EL, Belcher A, Atkinson A, Hill SL, Kawaguchi S, McCormack S, Meyer B, Nicol S, Ratnarajah L, Schmidt K, Steinberg DK, Tarling GA & Boyd PW (2019). The importance of Antarctic krill in biogeochemical cycles. *Nature Communications* 10:4742.

Cavanagh RD, Melbourne-Thomas J, Grant SM, Barnes DKA, Hughes KA, Halfter S, Meredith MP, Murphy EJ, Trebilco R & Hill SL (2021). Future risk for Southern Ocean ecosystem services under climate change. *Frontiers in Marine Science* 7:1224.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (1984). *Report of the third meeting of the scientific committee*, no. SC-CAMLR-III/11, CCAMLR, Hobart.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (2011). *Conservation measure 91-04 (2011): general framework for the establishment of CCAMLR marine protected areas*, CCAMLR, Hobart.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (2016). *Conservation measure 91-05 (2016): Ross Sea region marine protected area*, CCAMLR, Hobart.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (2017). *Krill fishery report 2017*, CCAMLR, Hobart.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (2019). *Report of the thirty-eighth meeting of the scientific committee*, no. CCAMLR-38/32, CCAMLR, Hobart.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (2020). Fishery reports online database, CCAMLR, Hobart, http://fisheryreports.ccamlr.org.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (2021a). CCAMLR statistical bulletin, vol. 32 (dataset), CCAMLR, Hobart, https://www.ccamlr.org/en/document/data/ccamlr-statistical-bulletin-vol-32.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (2021b). *Fishery report 2020: Euphausia superba in area 48*, CCAMLR, Hobart.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) (2021c). *Fishery report 2020: Champsocephalus gunnari in subarea 48.3*, CCAMLR, Hobart.

CEP (Committee for Environmental Protection) (2011). *Non-native species manual*, Secretariat of the Antarctic Treaty, Buenos Aires, Argentina.

Cheng CHC, Liangbiao C, Near TJ & Jin Y (2003). Functional antifreeze glycoprotein genes in temperate water New Zealand nototheniid fish infer an Antarctic evolutionary origin. *Molecular Biology and Evolution* 20(11):1897–1908.

Chittleborough RG (1965). Dynamics of two populations of the humpback whale, *Megaptera novaeangliae* (Borowski). *Australian Journal of Marine and Freshwater Research* 16(1):33–128.

Chiuchiolo AL, Dickhut RM, Cochran MA & Ducklow HW (2004). Persistent organic pollutants at the base of the Antarctic marine food web. *Environmental Science & Technology* 38(13):3551–3557.

Chong CW, Pearce DA, Convey P, Tan GYA, Wong RCS & Tan IKP (2010). High levels of spatial heterogeneity in the biodiversity of soil prokaryotes on Signy Island, Antarctica. *Soil Biology and Biochemistry* 42(4):601–610.

Chown SL (2017). Antarctic environmental challenges in a global context. In: Dodds K, Hemmings AD & Roberts P (eds), *Handbook on the politics of Antarctica*, Edward Elgar Publishing, Cheltenham, United Kingdom, 523–539.

Chu WL, Dang NL, Kok YY, Ivan Yap KS, Phang SM & Convey P (2019). Heavy metal pollution in Antarctica and its potential impacts on algae. *Polar Science* 20(Part 1):75–83.

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D & Unnikrishnan AS (2013). Sea level change. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (eds), *Climate change 2013: the physical science basis*, Cambridge University Press, Cambridge, United Kingdom and New York, United States, 1137–1216.

Chwedorzewska KJ (2008). *Poa annua* L. in Antarctic: searching for the source of introduction. *Polar Biology* 31(3):263–268.

Clapham PJ & Scott Baker C (2018). Whaling, modern. In: Würsig B, Thewissen JGM & Kovacs KM (eds), *Encyclopedia of marine mammals*, 3rd edn, Academic Press, London, 1070–1074.

Clark GF, Marzinelli EM, Fogwill CJ, Turney CSM & Johnston EL (2015). Effects of sea-ice cover on marine benthic communities: a natural experiment in Commonwealth Bay, East Antarctica. *Polar Biology* 38(8):1213–1222.

Clark GF, Stark JS, Palmer AS, Riddle MJ & Johnston EL (2017). The roles of sea-ice, light and sedimentation in structuring shallow Antarctic benthic communities. *PLOS ONE* 12(1):e0168391.

Clark L (2003). *Macquarie Island: a conservation assessment*, unpublished report to the Australian Antarctic Division, Australian Antarctic Division, Kingston, Tasmania.

Clarke LJ, Robinson SA, Hua Q, Ayre DJ & Fink D (2012). Radiocarbon bomb spike reveals biological effects of Antarctic climate change. *Global Change Biology* 18(1):301–310.

Clausius E, McMahon CR & Hindell MA (2017). Five decades on: use of historical weaning size data reveals that a decrease in maternal foraging success underpins the long-term decline in population of southern elephant seals (*Mirounga leonina*). *PLOS ONE* 12(3):e0173427.

Cleeland JB (2018). *Factors that drive demographic change in a community of albatrosses*, PhD thesis, University of Tasmania, Hobart.

Clem KR & Fogt RL (2015). South Pacific circulation changes and their connection to the tropics and regional Antarctic warming in austral spring, 1979–2012. *Journal of Geophysical Research: Atmospheres* 120(7):2773–2792.

Clem KR, Renwick JA & McGregor J (2018). Autumn cooling of western East Antarctica linked to the tropical Pacific. *Journal of Geophysical Research: Atmospheres* 123(1):89–107.

Coetzee BWT, Convey P & Chown SL (2017). Expanding the protected area network in Antarctica is urgent and readily achievable. *Conservation Letters* 10(6):670–680.

COMNAP (Council of Managers of National Antarctic Programs) (2008). *COMNAP fuel manual*, version 1.0, COMNAP, Hobart.

COMNAP (Council of Managers of National Antarctic Programs) (2017). *Antarctic station catalogue*, COMNAP, Christchurch.

COMNAP (Council of Managers of National Antarctic Programs) (2019). *Report on the extent of sewage treatment plant infestations across the Antarctic Treaty area: survey results*, no. IP 38, Secretariat of the Antarctic Treaty, Buenos Aires, Argentina.

Constable AJ (2002). The status of Antarctic fisheries research. In: Jabour-Green J & Haward M (eds), *The Antarctic: past, present and future*, Antarctic CRC research report #28, Antarctic Cooperative Research Centre, Hobart, 71–84.

Constable AJ, Melbourne-Thomas J, Corney SP, Arrigo KR, Barbraud C, Barnes DKA et al. (2014). Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. *Global Change Biology* 20(10):3004–3025.

Convey P (1996). Reproduction of Antarctic flowering plants. *Antarctic Science* 8(2):127–134.

Convey P, Gibson JA, Hillenbrand CD, Hodgson DA, Pugh PJ, Smellie JL & Stevens MI (2008). Antarctic terrestrial life – challenging the history of the frozen continent? *Biological Reviews of the Cambridge Philosophical Society* 83(2):103–117.

Convey P, Chown SL, Clarke A, Barnes DKA, Bokhorst S, Cummings VJ et al. (2014). The spatial structure of Antarctic biodiversity. *Ecological Monographs* 84(2):203–244.

Convey P & Peck LS (2019). Antarctic environmental change and biological responses. *Science Advances* 5(11):eaaz0888.

Cook AJ, Fox AJ, Vaughan DG & Ferrigno JG (2005). Retreating glacier fronts on the Antarctic Peninsula over the past half-century. *Science* 308(5721):541–544.

Cook AJ & Vaughan DG (2010). Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. *The Cryosphere* 4(1):77–98.

Cooke JG (2018). Antarctic blue whale: *Balaenoptera musculus* ssp. *intermedia*. The IUCN red list of threatened species 2018: e.T41713A50226962, International Union for Conservation of Nature, Cambridge, United Kingdom, accessed 11 May 2021, https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T41713A50226962.en.

Copson GR (1984). *ANARE research notes*, vol. 18, *An annotated atlas of the vascular flora of Macquarie Island*, Antarctic Division, Department of Science and Technology, Kingston, Tasmania.

Corbett PA, King CK, Stark JS & Mondon JA (2014). Direct evidence of histopathological impacts of wastewater discharge on resident Antarctic fish (*Trematomus bernacchii*) at Davis Station, East Antarctica. *Marine Pollution Bulletin* 87(1–2):48–56.

Corsolini S, Romeo T, Ademollo N, Greco S & Focardi S (2002). POPs in key species of marine Antarctic ecosystem. *Microchemical Journal* 73(1):187–193.

Corsolini S, Ademollo N, Martellini T, Randazzo D, Vacchi M & Cincinelli A (2017). Legacy persistent organic pollutants including PBDEs in the trophic web of the Ross Sea (Antarctica). *Chemosphere* 185:699–708.

Cowan DA, Russell NJ, Mamais A & Sheppard DM (2002). Antarctic Dry Valley mineral soils contain unexpectedly high levels of microbial biomass. *Extremophiles* 6(5):431–436.

Davey MP, Norman L, Sterk P, Huete-Ortega M, Bunbury F, Loh BKW, Stockton S, Peck LS, Convey P, Newsham KK & Smith AG (2019). Snow algae communities in Antarctica: metabolic and taxonomic composition. *New Phytologist* 222(3):1242–1255.

Davidson A & Belbin L (2002). Exposure of natural Antarctic marine microbial assemblages to ambient UV radiation: effects on the marine microbial community. *Aquatic Microbial Ecology* 27(2):159–174.

DAWE (Australian Government Department of Agriculture, Water and the Environment) (2020a). Environmental performance reporting, DAWE, Canberra, accessed 27 May 2021, https://www.awe.gov.au/about/reporting/annual-report/environmental-performance.

DAWE (Australian Government Department of Agriculture, Water and the Environment) (2020b). *Department of Agriculture, Water and the Environment annual report 2019–20*, DAWE, Canberra.

DAWE (Australian Government Department of Agriculture, Water and the Environment) (2021a). Draft National Recovery Plan for albatrosses and petrels (2021), DAWE, Canberra, accessed 5 Jun 2021, https://www.environment.gov.au/biodiversity/threatened/recovery-plans/comment/draft-recovery-plan-albatrosses-petrels-2021.

DAWE (Australian Government Department of Agriculture, Water and the Environment) (2021b). *Consultation document on eligibility for delisting Megaptera novaeangliae (humpback whale)*, DAWE, Canberra.

(DAWE) Australian Government Department of Agriculture, Water and the Environment. Heritage, Australian Government, Canberra, 25 October, https://www.awe.gov.au/parks-heritage/heritage.

De Broyer C & Danis B (2011). How many species in the Southern Ocean? Towards a dynamic inventory of the Antarctic marine species. *Deep-Sea Research Part II: Topical Studies in Oceanography* 58(1–2):5–17.

de Menezes GCA, Porto BA, Amorim SS, Zani CL, de Almeida Alves TM, Junior PAS, Murta SMF, Simões JC, Cota BB, Rosa CA & Rosa LH (2020). Fungi in glacial ice of Antarctica: diversity, distribution and bioprospecting of bioactive compounds. *Extremophiles* 24(3):367–376.

de Sousa JRP, Gonçalves VN, de Holanda RA, Santos DA, Bueloni CFLG, Costa AO, Petry MV, Rosa CA & Rosa LH (2017). Pathogenic potential of environmental resident fungi from ornithogenic soils of Antarctica. *Fungal Biology* 121(12):991–1000.

DeConto RM & Pollard D (2003). Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. *Nature* 421(6920):245–249.

DEE (Australian Government Department of the Environment and Energy) (2018). *Threat abatement plan for the impacts of marine debris on the vertebrate wildlife of Australia's coasts and oceans*, DEE, Canberra.

DEE (Australian Government Department of the Environment and Energy) (2019). *Department of the Environment and Energy 2018–19 annual report environmental indicators*, DEE, Canberra.

Deppeler SL & Davidson AT (2017). Southern Ocean phytoplankton in a changing climate. *Frontiers in Marine Science* 4:40.

Dhomse SS, Kinnison D, Chipperfield MP, Salawitch RJ, Cionni I, Hegglin MI et al. (2018). Estimates of ozone return dates from chemistry-climate model initiative simulations. *Atmospheric Chemistry and Physics* 18(11):8409–8438.

Dias MP, Martin R, Pearmain EJ, Burfield IJ, Small C, Phillips RA, Yates O, Lascelles B, Garcia Borboroglu P & Croxall JP (2019). Threats to seabirds: a global assessment. *Biological Conservation* 237:525–537.

Dick AL (1991). Concentrations and sources of metals in the Antarctic Peninsula aerosol. *Geochimica et Cosmochimica Acta* 55(7):1827–1836.

Dickson CR, Baker DJ, Bergstrom DM, Bricher PK, Brookes RH, Raymond B, Selkirk PM, Shaw JD, Terauds A, Whinam J & McGeoch MA (2019). Spatial variation in the ongoing and widespread decline of a keystone plant species. *Austral Ecology* 44(5):891–905.

Dickson CR, Baker DA, Bergstrom DM, Brookes RH, Whinam J & McGeoch MA (2021). Widespread dieback in a foundation species on a sub-Antarctic World Heritage Island: fine-scale patterns and likely drivers. *Austral Ecology* 46:52–64.

Dilley B, Schoombie S, Stevens K, Davies D, Perold V, Osborne A, Schoombie J, Brink C, Carpenter-Kling T & Ryan P (2017). Mouse predation affects breeding success of burrow-nesting petrels at sub-Antarctic Marion Island. *Antarctic Science* 30(2):93–104.

Doddridge EW & Marshall J (2017). Modulation of the seasonal cycle of Antarctic sea ice extent related to the Southern Annular Mode. *Geophysical Research Letters* 44(19):9761–9768.

Doney SC, Tilbrook B, Roy S, Metzl N, Le Quéré C, Hood M, Feely RA & Bakker D (2009). Surface-ocean CO_2 variability and vulnerability. *Deep-Sea Research Part II: Topical Studies in Oceanography* 56(8–10):504–511.

Doney SC, Busch DS, Cooley SR & Kroeker KJ (2020). The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annual Review of Environment and Resources* 45:83–112.

Donoghue S & Harris U (2017). *Fluctuations of Heard Island glaciers 2012–2014*, Australian Antarctic Division internal report, Australian Antarctic Data Centre, Kingston, Tasmania.

Donoghue S (2021). *Heard Island glacier area change 2012–2016*, Australian Antarctic Division internal report, Australian Antarctic Data Centre, Kingston, Tasmania.

Ducklow HW, Fraser WR, Meredith MP, Stammerjohn. SE, Doney SC, Martinson DG, Sailley SF, Schofield OM, Steinberg DK, Venables HJ & Amsler CD (2013). West Antarctic Peninsula: an ice-dependent coastal marine ecosystem in transition. *Oceanography* 26(3):190–203.

Duffy GA & Lee JR (2019). Ice-free area expansion compounds the non-native species threat to Antarctic terrestrial biodiversity. *Biological Conservation* 232:253–257.

Duhamel G, Hulley PA, Causse R, Koubbi P, Vacchi M, Pruvost P et al. (2014). Biogeographic patterns of fish. In: De Broyer C, Koubbi P, Griffiths HJ, Raymond B, d'Udekem d'Acoz C, Van de Putte A, Danis B, David B, Grant S, Gutt J, Held C, Hosie G, Huettmann F, Post A & Ropert-Coudert Y (eds), *Biogeographic atlas of the Southern Ocean*, Scientific Committee on Antarctic Research, Cambridge, United Kingdom, 328–362.

Dunlop K, Barnes DKA & Bailey DM (2014). Variation of scavenger richness and abundance between sites of high and low iceberg scour frequency in Ryder Bay, west Antarctic Peninsula. *Polar Biology* 37(12):1741–1754.

Dunn MJ, Jackson JA, Adlard S, Lynnes AS, Briggs DR, Fox D & Waluda CM (2016). Population size and decadal trends of three penguin species nesting at Signy Island, South Orkney Islands. *PLOS ONE* 11(10):e0164025.

Dupont S, Ortega-Martínez O & Thorndyke M (2010). Impact of near-future ocean acidification on echinoderms. *Ecotoxicology* 19(3):449–462.

Durack PJ, Wijffels SE & Matear RJ (2012). Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science* 336(6080):455–458.

Eastman JT (1993). Physical and biological characteristics of the Antarctic marine environment. In: *Antarctic fish biology: evolution in a unique environment*, Academic Press, San Diego, 3–16.

Eastman JT (2005). The nature of the diversity of Antarctic fishes. *Polar Biology* 28(2):93–107.

Edwards TL, Nowicki S, Marzeion B, Hock R, Goelzer H, Seroussi H et al. (2021). Projected land ice contributions to twenty-first-century sea level rise. *Nature* 593(7857):74–82.

Ellis DS, Cipro CVZ, Ogletree CA, Smith KE & Aronson RB (2018). A 50-year retrospective of persistent organic pollutants in the fat and eggs of penguins of the Southern Ocean. *Environmental Pollution* 241:155–163.

Emslie SD, Polito MJ, Brasso R, Patterson WP & Sun L (2014). Ornithogenic soils and the paleoecology of pygoscelid penguins in Antarctica. *Quaternary International* 352:4–15.

England MH, Polvani L & Sun L (2018). Contrasting the Antarctic and Arctic atmospheric responses to projected sea ice loss in the late twenty-first century. *Journal of Climate* 31(16):6353–6370.

England MR, Polvani LM, Sun L & Deser C (2020). Tropical climate responses to projected Arctic and Antarctic sea-ice loss. *Nature Geoscience* 13(4):275–281.

Erickson AW, Siniff DB, Cline DR & Hofman RJ (1971). Distributional ecology of Antarctic seals. In: Deacon GER (ed), *Proceedings of the Symposium on Antarctic Ice and Water Masses*, Tokyo, 19 September 1970, Scientific Committee on Antarctic Research, Cambridge, United Kingdom, 55–76.

Erickson AW & Hanson MB (1990). Continental estimates and population trends of Antarctic ice seals. In: Kerry KR & Hempel G (eds), *Antarctic ecosystems*, Springer, Berlin, 253–264.

Ericson JA, Lamare MD, Morley SA & Barker MF (2010). The response of two ecologically important Antarctic invertebrates (*Sterechinus neumayeri* and *Parborlasia corrugatus*) to reduced seawater pH: effects on fertilisation and embryonic development. *Marine Biology* 157:2689–2702.

FAO (Food and Agriculture Organization of the United Nations) (2021). Agreement on Port State Measures (PSMA), FAO, Rome, accessed 12 May 2021, http://www.fao.org/port-state-measures/en/.

Fasullo JT, Nerem RS & Hamlington B (2016). Is the detection of accelerated sea level rise imminent? *Scientific Reports* 6:31245.

Favier V, Krinner G, Amory C, Gallée H, Beaumet J & Agosta C (2017). Antarctica-regional climate and surface mass budget. *Current Climate Change Reports* 3(4):303–315.

Feely R, Sabine CL, Lee K, Berelson W, Kleypas J, Fabry VJ & Millero FJ (2004). Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science* 305(5682):362–366.

Fernández PM, Martorell MM, Blaser MG, Ruberto LAM, de Figueroa LIC & Mac Cormack WP (2017a). Phenol degradation and heavy metal tolerance of Antarctic yeasts. *Extremophiles* 21(3):445–457.

Fernández PM, Martorell MM, Blaser MG, Ruberto LAM, de Figueroa LIC & Mac Cormack WP (2017b). Phenol degradation and heavy metal tolerance of Antarctic yeasts. *Extremophiles* 21(3):445-457.

Figuerola B, Hancock AM, Bax N, Cummings VJ, Downey R, Griffiths HJ, Smith J & Stark JS (2021). A review and meta-analysis of potential impacts of ocean acidification on marine calcifiers from the Southern Ocean. *Frontiers in Marine Science* 8:584445.

Fisher M (2014). Spotlight back on Antarctica's peculiar soils as scientists study climate change effects. *Soil Horizons* 55(2):sh2014-55-2-f.

Fitzgerald NB, Kirkpatrick JB & Scott JJ (2021). Rephotography, permanent plots and remote sensing data provide varying insights on vegetation change on subantarctic Macquarie Island, 1980–2015. *Austral Ecology* 46(5):762–775.

Fogt RL & Marshall GJ (2020). The Southern Annular Mode: variability, trends, and climate impacts across the Southern Hemisphere. *WIREs Climate Change* 11(4):e652.

Fogwill CJ, Turney CSM, Menviel L, Baker A, Weber ME, Ellis B et al. (2020). Southern Ocean carbon sink enhanced by sea-ice feedbacks at the Antarctic Cold Reversal. *Nature Geoscience* 13(7):489–497.

Forgati M, Kandalski PK, Herrerias T, Zaleski T, Machado C, Souza MRDP & Donatti L (2017). Effects of heat stress on the renal and branchial carbohydrate metabolism and antioxidant system of Antarctic fish. *Journal of Comparative Physiology B* 187(8):1137–1154.

Fraser AD, Massom RA, Michael KJ, Galton-Fenzi BK & Lieser JL (2012). East Antarctic landfast sea ice distribution and variability, 2000–2008. *Journal of Climate* 25(4):1137–1156.

Fraser AD, Massom RA, Ohshima KI, Willmes S, Kappes PJ, Cartwright J & Porter-Smith R (2020). High-resolution mapping of circum-Antarctic landfast sea ice distribution, 2000–2018. *Earth System Science Data* 12(4):2987–2999.

Fraser CI, Morrison AK, Hogg AMC, Macaya EC, van Sebille E, Ryan PG, Padovan A, Jack C, Valdivia N & Waters JM (2018). Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. *Nature Climate Change* 8:704–708.

French WJR, Mulligan FJ & Klekociuk AR (2020a). Analysis of 24 years of mesopause region OH rotational temperature observations at Davis, Antarctica – part 1: long-term trends. *Atmospheric Chemistry and Physics* 20(11):6379–6394.

French WJR, Klekociuk AR & Mulligan FJ (2020b). Analysis of 24 years of mesopause region OH rotational temperature observations at Davis, Antarctica – part 2: evidence of a quasi-quadrennial oscillation (QQO) in the polar mesosphere. *Atmospheric Chemistry and Physics* 20(14):8691–8708.

Frenot Y, Chown SL, Whinam J, Selkirk PM, Convey P, Skotnicki M & Bergstrom DM (2005). Biological invasions in the Antarctic: extent, impacts and implications. *Biological Reviews* 80(1):45–72.

Fretwell P, Pritchard HD, Vaughan DG, Bamber JL, Barrand NE, Bell R et al. (2013). Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere* 7(1):375–393.

Fretwell P & Trathan P (2019). Emperors on thin ice: three years of breeding failure at Halley Bay. *Antarctic Science* 31(3):133–138.

Fretwell PT, Ratcliffe N, Fox AJ, Fleming AH, Trathan PN, LaRue MA, Morin P, Porter C, Kooyman GL & Wienecke B (2012). An emperor penguin population estimate: the first global, synoptic survey of a species from space. *PLOS ONE* 7(4):e33751.

Fretwell PT, Trathan PN, Wienecke B & Kooyman GL (2014). Emperor penguins breeding on iceshelves. *PLOS ONE* 9(1):e85285.

Fretwell PT & Trathan PN (2020). Discovery of new colonies by Sentinel2 reveals good and bad news for emperor penguins. *Remote Sensing in Ecology and Conservation* 7(2):139–153.

Frugone MJ, Lowther A, Noll D, Ramos B, Pistorius P, Dantas GPM et al. (2018). Contrasting phylogeographic pattern among *Eudyptes* penguins around the Southern Ocean. *Scientific Reports* 8(1):17481.

Galeotti S, DeConto R, Naish T, Stocchi P, Florindo F, Pagani M, Barrett P, Bohaty SM, Lanci L, Pollard D, Sandroni S, Talarico FM & Zachos JC (2016). Antarctic ice sheet variability across the Eocene-Oligocene boundary climate transition. *Science* 352(6281):76–80.

Gardner AS, Moholdt G, Scambos T, Fahnstock M, Ligtenberg S, van den Broeke M & Nilsson J (2018). Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years. *The Cryosphere* 12(2):521–547.

George JL & Frear DEH (1966). Pesticides in the Antarctic. *Journal of Applied Ecology* 3(Suppl):155–167.

GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) (2001). *Protecting the oceans from land-based activities*, United Nations Environment Programme, Arendal, Norway.

Gibson JAE, Dartnall HJG & Swadling KM (1998). On the occurrence of males and production of ephippial eggs in populations of *Daphniopsis studeri* (Cladocera) in lakes of the Vestfold and Larsemann Hills, East Antarctica. *Polar Biology* 19:148–150.

Gibson JAE (1999). The meromictic lakes and stratified marine basins of the Vestfold Hills, East Antarctica. *Antarctic Science* 11(2):175–192.

Gillett NP, Kell TD & Jones PD (2006). Regional climate impacts of the Southern Annular Mode. *Geophysical Research Letters* 33(23):L23704.

Gilmour ME, Holmes ND, Fleishman AB & Kriwoken LK (2019). Temporal and interspecific variation in feather mercury in four penguin species from Macquarie Island, Australia. *Marine Pollution Bulletin* 142:282–289.

Global Volcanism Program, Bennis KL & Venzke E (2020). Report on Heard (Australia). In: *Bulletin of the Global Volcanism Network*, vol. 45, no. 5, Smithsonian Institution, Washington.

Goessling HF & Bathiany S (2016). Why CO_2 cools the middle atmosphere – a consolidating model perspective. *Earth Systems Dynamics* 7(3):697–715.

Goetz KT, Burns JM, Hückstädt LA, Shero MR & Costa DP (2017). Temporal variation in isotopic composition and diet of Weddell seals in the western Ross Sea. *Deep-Sea Research Part II: Topical Studies in Oceanography* 140:36–44.

Golledge NR, Naish TR, Levy RH, Kowalewski DE, Fogwill CJ & Gasson EGW (2015). The multi-millennial Antarctic commitment to future sea-level rise. *Nature* 526(7573):421–425.

Golubev S (2020). Macroplastic in seabirds at Mirny, Antarctica. *Birds* 1(1):13–18.

Gomes ECQ, Godinho VM, Silva DAS, de Paula MTR, Vitoreli GA, Zani CL et al. (2018). Rapid change in east Antarctic terrestrial vegetation in response to regional drying. *Nature Climate Change* 8(10):879–884.

Gore DB, Revill AT & Guille D (1999). Petroleum hydrocarbons ten years after spillage at a helipad in Bunger Hills, East Antarctica. *Antarctic Science* 11:427-429.

Gray A, Krolikowski M, Fretwell P, Convey P, Peck LS, Mendelova M, Smith AG & Davey MP (2020). Remote sensing reveals Antarctic green snow algae as important terrestrial carbon sink. *Nature Communications* 11:2527.

Green TGA, Sancho LG, Pintado A & Schroeter B (2011). Functional and spatial pressures on terrestrial vegetation in Antarctica forced by global warming. *Polar Biology* 34(11):1643-1656.

Greenslade P, Stevens MI & Edwards R (2007). Invasion of two exotic terrestrial flatworms to subantarctic Macquarie Island. *Polar Biology* 30:961–967.

Greenslade P, Melbourne BA, Davies KF & Stevens MI (2008). The status of two exotic terrestrial Crustacea on sub-Antarctic Macquarie Island. *Polar Record* 44(228):15–23.

Grieger J, Leckebusch GC & Ulbrich U (2016). Net precipitation of Antarctica: thermodynamical and dynamical parts of the climate change signal. *Journal of Climate* 29(3):907–924.

Grotti M, Pizzini S, Abelmoschi ML, Cozzi G, Piazza R & Soggia F (2016). Retrospective biomonitoring of chemical contamination in the marine coastal environment of Terra Nova Bay (Ross Sea, Antarctica) by environmental specimen banking. *Chemosphere* 165:418–426.

Gudmundsson GH, Paolo FS, Adusumilli S & Fricker HA (2019). Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves. *Geophysical Research Letters* 46(23):13903–13909.

Guo LW (2020). Worried about hair loss? So are these seals. *Conservation Physiology* 8(1):coaa072.

Guyomard AI (2010). Ethics and bioprospecting in Antarctica. *Ethics in Science and Environmental Politics* 10(1):31–44.

Gwyther DE, O'Kane TJ, Galton-Fenzi BK, Monselesan DP & Greenbaum JS (2018). Intrinsic processes drive variability in basal melting of the Totten Glacier Ice Shelf. *Nature Communications* 9(1):3141.

Hammond MD & Jones DC (2016). Freshwater flux from ice sheet melting and iceberg calving in the Southern Ocean. *Geoscience Data Journal* 3(2):60–62.

Hanchet S, Dunn A, Parker S, Horn P, Stevens D & Mormede S (2015). The Antarctic toothfish (*Dissostichus mawsoni*): biology, ecology, and life history in the Ross Sea region. *Hydrobiologia* 761(1):397–414.

Hanchet SM, Mormede S & Dunn A (2010). Distribution and relative abundance of Antarctic toothfish (*Dissostichus mawsoni*) on the Ross Sea shelf. *CCAMLR Science* 17:33–51.

Hancock AM, King CK, Stark JS, McMinn A & Davidson AT (2020). Effects of ocean acidification on Antarctic marine organisms: a meta-analysis. *Ecology and Evolution* 10(10):4495–4514.

Harris CM, Lorenz K, Fishpool LDC, Lascelles B, Cooper J, Coria NR et al. (2015). *Important bird areas in Antarctica 2015*, BirdLife International & Environmental Research and Assessment, Cambridge, United Kingdom.

Harris U (2018). Heard Island digitising 2009 (dataset), Australian Antarctic Data Centre, Kingston, Tasmania, https://data.aad.gov.au/metadata/records/Heard_Island_digitising_2009.

Hartmann DL, Tank AMK, Rusticucci M, Alexander LV, Brönnimann S, Charabi YAR, Dentener FJ, Dlugokencky EJ, Easterling DR, Kaplan A, Soden BJ, Thorne PW, Wild M & Zhai P (2013). Observations: atmosphere and surface. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (eds), *Climate change 2013: the physical science basis*, Cambridge University Press, Cambridge, United Kingdom and New York, United States, 159–254.

Hattermann T, Nicholls KW, Hellmer HH, Davis PED, Janout MA, Østerhus S, Schlosser E, Rohardt G & Kanzow T (2021). Observed interannual changes beneath Filchner-Ronne Ice Shelf linked to large-scale atmospheric circulation. *Nature Communications* 12:2961.

Haumann FA, Notz D & Schmidt H (2014). Anthropogenic influence on recent circulation-driven Antarctic sea ice changes. *Geophysical Research Letters* 41(23):8429–8437.

Haumann FA, Gruber N, Münnich M, Frenger I & Kern S (2016). Sea-ice transport driving Southern Ocean salinity and its recent trends. *Nature* 537(7618):89–92.

Haumann FA, Gruber N & Münnich M (2020). Sea-ice induced Southern Ocean subsurface warming and surface cooling in a warming climate. *AGU Advances* 1(2):e2019AV000132.

Hayashida H, Matear RJ, Strutton PG & Zhang X (2020). Insights into projected changes in marine heatwaves from a high-resolution ocean circulation model. *Nature Communications* 11:4352.

Heerah K, Hindell M, Andrew-Goff V, Field I, McMahon CR & Charrassin JB (2016). Contrasting behavior between two populations of an ice-obligate predator in East Antarctica. *Ecology and Evolution* 7(2):606–618.

Helm KP, Bindoff NL & Church JA (2010). Changes in the global hydrological-cycle inferred from ocean salinity. *Geophysical Research Letters* 37(18):L18701.

Hemmings AD & Rogan-Finnemore M (2008). Access, obligations, and benefits: regulating bioprospecting in the Antarctic. In: Firestone J, Bubna-Litic K & Jeffery MI (eds), *Biodiversity, conservation, law and livelihoods: bridging the north-south divide*, Cambridge University Press, United Kingdom, 529–552.

Hendriks IE, Duarte CM & Álvarez M (2010). Vulnerability of marine biodiversity to ocean acidification: a meta-analysis. *Estuarine, Coastal and Shelf Science* 86(2):157–164.

Hindell MA, McMahon CR, Bester MN, Boehme L, Costa DP, Fedak MA et al. (2016). Circumpolar habitat use in the southern elephant seal: implications for foraging success and population trajectories. *Ecosphere* 7(5):e01213.

Hobbs W, Curran M, Abram N & Thomas ER (2016a). Century-scale perspectives on observed and simulated Southern Ocean sea ice trends from proxy reconstructions. *Journal of Geophysical Research: Oceans* 121(10):7804–7818.

Hobbs WR, Massom R, Stammerjohn S, Reid P, Williams GD & Meier W (2016b). A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change* 143:228–250.

Hogg AMC, Spence P, Saenko OA & Downes SM (2017). The energetics of Southern Ocean upwelling. *Journal of Physical Oceanography* 47(1):135–153.

Hogg CJ, Lea MA, Gual Soler M, Vasquez VN, Payo-Payo A, Parrott ML, Santos MM, Shaw J & Brooks CM (2020). Protect the Antarctic Peninsula – before it's too late. *Nature* 586(7830):496–499.

Holbrook NJ, Scannell HA, Sen Gupta A, Benthuysen JA, Feng M, Oliver ECJ et al. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications* 10:2624.

Holbrook NJ, Sen Gupta A, Oliver ECJ, Hobday AJ, Benthuysen JA, Scannell HA, Smale DA & Wernberg T (2020). Keeping pace with marine heatwaves. *Nature Reviews Earth and Environment* 1(9):482–493.

Holland DM, Nicholls KW & Basinski A (2020). The Southern Ocean and its interaction with the Antarctic ice sheet. *Science* 367(6484):1326–1330.

Holland PR & Kwok R (2012). Wind-driven trends in Antarctic sea ice motion. *Nature Geoscience* 5(12):872–875.

Holland PR (2014). The seasonality of Antarctic sea ice trends. *Geophysical Research Letters* 41(12):4230–4237.

Houghton M, McQuillan PB, Bergstrom DM, Frost L, van den Hoff J & Shaw J (2016). Pathways of alien invertebrate transfer to the Antarctic region. *Polar Biology* 39:23–33.

Hückstädt LA, Burnes JM, Koch PL, McDonald BI, Crocker DE & Costa DP (2012). Diet of a specialist in a changing environment: the crabeater seal along the western Antarctic Peninsula. *Marine Ecology Progress Series* 455:287–301.

Hückstädt LA, Piñones A, Palacios DM, McDonald BI, Dinniman MS, Hofmann EE, Burnes JM, Crocker DE & Costa DP (2020). Projected shifts in the foraging habitat of crabeater seals along the Antarctic Peninsula. *Nature Climate Change* 10(5):472–477.

Hughes JMR (1987). The distribution and composition of vascular plant communities on Heard Island. *Polar Biology* 7(3):153–162.

Hughes KA, Cowan DA & Wilmotte A (2015). Protection of Antarctic microbial communities: 'out of sight, out of mind'. *Frontiers in Microbiology* 6:151.

Hughes KA, Pescott OL, Peyton J, Adriaens T, Cottier-Cook EJ, Key G et al. (2020). Invasive non-native species likely to threaten biodiversity and ecosystems in the Antarctic Peninsula region. *Global Change Biology* 26(4):2702–2716.

Hugonnet R, McNabb R, Berthier E, Menounos B, Nuth C, Girod L, Farinotti D, Huss M, Dussaillant I, Brun F & Kääb A (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature* 592(7856):726–731.

Humbert A, Gross D, Müller R, Braun M, van de Wal RSW, van den Broeke MR, Vaughan DG & van den Berg WJ (2010). Deformation and failure of the ice bridge on the Wilkins Ice Shelf, Antarctica. *Annals of Glaciology* 51(55):49–55.

Hunt BM, Hoefling K & Cheng CHC (2003). Annual warming episodes in seawater temperatures in McMurdo Sound in relationship to endogenous ice in notothenioid fish. *Antarctic Science* 15(3):333–338.

Hutchins DA, Mulholland MR & Fu F (2009). Nutrient cycles and marine microbes in a CO_2-enriched ocean. *Oceanography* 22(4):128–145.

IAATO (International Association of Antarctic Tour Operators) (2021). Data and statistics, IAATO, accessed 12 May 2021, https://iaato.org/information-resources/data-statistics/.

Iakovenko NS, Smykla J, Convey P, Kašparová E, Kozeretska IA, Trokhymets V, Dykyy I, Plewka M, Devetter M, Duriš Z & Janko K (2015). Antarctic bdelloid rotifers: diversity, endemism and evolution. *Hydrobiologia* 761(1):5–43.

Ibañez AE, Morales LM, Torres DS, Borghello P, Haidr NS & Montalti D (2020). Plastic ingestion risk is related to the anthropogenic activity and breeding stage in an Antarctic top predator seabird species. *Marine Pollution Bulletin* 157:111351.

IMBIE team (2018). Mass balance of the Antarctic ice sheet from 1992 to 2017. *Nature* 558(7709):219–222.

IMO (International Maritime Organization) (2019). Shipping in polar waters, IMO, London, accessed 12 May 2021, https://www.imo.org/en/MediaCentre/HotTopics/Pages/Polar-default.aspx.

IMOS (Integrated Marine Observing System) (2021). *Integrated Marine Observing System*, University of Tasmania, Hobart, accessed 1 Sep 2021, https://imos.org.au/.

IPCC (Intergovernmental Panel on Climate Change) (2013). Summary for policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (eds), *Climate change 2013: the physical science basis*, Cambridge University Press, Cambridge, United Kingdom and New York, United States, 1–30.

IPCC (Intergovernmental Panel on Climate Change) (in press-a). *IPCC special report on the ocean and cryosphere in a changing climate*, Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B & Weyer NM (eds), Intergovernmental Panel on Climate Change, Switzerland.

IPCC (Intergovernmental Panel on Climate Change) (in press-b). Summary for policymakers. In: Massom-Delmotte VP, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen L, Goldfarb MI, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R & Zhou B (eds), *Climate change 2021: the physical science basis*, Cambridge University Press, Cambridge, United Kingdom.

IUCN (International Union for Conservation of Nature and Natural Resources) (2021). *The IUCN Red List of Threatened Species*, IUCN, Cambridge, United Kingdom, https://www.iucnredlist.org.

IWC (International Whaling Commission) (1995). *Forty-fifth report of the International Whaling Commission*, IWC, Cambridge, United Kingdom.

IWC (International Whaling Commission) (2021). Humpback whale – *Megaptera novaeangliae*, IWC, Cambridge, United Kingdom, accessed 27 May 2021, https://iwc.int/humpback-whale.

Jacobs S, Jenkins A, Hellmer H, Giulivi CF, Nitsche F, Huber B & Guerrero R (2012). The Amundsen Sea and the Antarctic ice sheet. *Oceanography* 25(3):154–263.

Jenouvrier S, Che-Castaldo J, Wolf S, Holland M, Labrousse S, LaRue M, Wienecke B, Fretwell P, Barbraud C, Greenwalk N, Stroeve J & Trathan PN (2021). The call of the emperor penguin: legal responses to species threatened by climate change. *Global Change Biology* 27(20):5008–5029.

Jerez S, Motas M, Benzal J, Diaz J & Barbosa A (2013). Monitoring trace elements in Antarctic penguin chicks from South Shetland Islands, Antarctica. *Marine Pollution Bulletin* 69(1–2):67–75.

Ji M, Greening C, Vanwonterghem I, Carere CR, Bay SK, Steen JA, Montgomery K, Lines T, Beardall J, van Dorst J, Snape I, Stott MB, Hugenholtz P & Ferrari BC (2017). Atmospheric trace gases support primary production in Antarctic desert surface soil. *Nature* 552(7685):400–403.

Jones CW, Risi MM, Cleeland J & Ryan PG (2019). First evidence of mouse attacks on adult albatrosses and petrels breeding on sub-Antarctic Marion and Gough Islands. *Polar Biology* 42:619–623.

Jones JM, Gille ST, Goosse H, Abram NJ, Canziani PO, Charman DJ et al. (2016). Assessing recent trends in high-latitude Southern Hemisphere surface climate. *Nature Climate Change* 6(10):917–926.

Joughin I & Alley RB (2011). Stability of the West Antarctic Ice Sheet in a warming world. *Nature Geoscience* 4(8):506–513.

Jouzel J, Masson-Delmotte V, Cattani O, Dreyfus G, Falourd S, Hoffmann G et al. (2007). Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science* 317(5839):793–796.

Kacimi S & Kwok R (2020). The Antarctic sea ice cover from ICESat-2 and CryoSat-2: freeboard, snow depth, and ice thickness. *The Cryosphere* 14(12):4453–4474.

Kawaguchi S, Nicol S & Press AJ (2009). Direct effects of climate change on the Antarctic krill fishery. *Fisheries Management and Ecology* 16(5):424–427.

Kawaguchi S, Ishida A, King R, Raymond B, Waller N, Constable A, Nicol S, Wakita M & Ishimatsu A (2013). Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nature Climate Change* 3(9):843–847.

Kawarasaki Y, Teets NM, Philip BN, Potts LJ, Gantz JD, Denlinger DL & Lee RE (2019). Characterization of drought-induced rapid cold-hardening in the Antarctic midge, *Belgica antarctica*. *Polar Biology* 42(6):1147–1156.

Kennedy AD (1993). Water as a limiting factor in the Antarctic terrestrial environment: a biogeographical synthesis. *Arctic and Alpine Research* 25(4):308–315.

Kent CS, Jenner C, Jenner M, Bouchet P & Rexstad E (2012). Southern Hemisphere breeding stock D humpback whale population estimates from North West Cape, Western Australia. *Journal of Cetacean Research and Management* 12(1):29–38.

Keppler L & Landschützer P (2019). Regional wind variability modulates the Southern Ocean carbon sink. *Scientific Reports* 9(1):7384.

Khan AL, Dierssen HM, Scambos TA, Höfer J & Cordero RR (2021). Spectral characterization, radiative forcing and pigment content of coastal Antarctic snow algae: approaches to spectrally discriminate red and green communities and their impact on snowmelt. *The Cryosphere* 15(1):133–148.

Kim JT, Choi YJ, Barghi M, Kim JH, Jung JW, Kim K, Kang JH, Lammel G & Chang YS (2021). Occurrence, distribution, and bioaccumulation of new and legacy persistent organic pollutants in an ecosystem on King George Island, maritime Antarctica. *Journal of Hazardous Materials* 405:124141.

King DH (2017). *Monitoring Antarctic bryophyte communities in a time of change*, PhD thesis, University of Wollongong, Wollongong.

Klein RD, Rosa CE, Colares EP, Robaldo RB, Martinez PE & Bianchini A (2017). Antioxidant defense system and oxidative status in Antarctic fishes: the sluggish rockcod *Notothenia coriiceps* versus the active marbled notothen *Notothenia rossii*. *Journal of Thermal Biology* 68(Part A):119–127.

Klekociuk AR & Wienecke B (2016). Antarctic environment. In: *Australia state of the environment 2016*, Australian Government Department of the Environment and Energy, Canberra.

Klekociuk AR, Tully MB, Krummel PB, Henderson SI, Smale D, Querel R, Nichol S, Alexander SP, Fraser PJ & Nedoluha G (2021). The Antarctic ozone hole during 2018 and 2019. *Journal of Southern Hemisphere Earth Systems Science* 71(1):66–91.

Kohlbach D, Lange BA, Graeve M, Vortkamp M & Flores H (2019). Varying dependency of Antarctic euphausiids on ice algae- and phytoplankton-derived carbon sources during summer. *Marine Biology* 166:79.

Koppel DJ, Adams MS, King CK & Jolley DF (2019). Preliminary study of cellular metal accumulation in two Antarctic marine microalgae: implications for mixture interactivity and dietary risk. *Environmental Pollution* 252(Part B):1582–1592.

Kostov Y, Ferreira D, Armour KC & Marshall J (2018). Contributions of greenhouse gas forcing and the southern annular mode to historical Southern Ocean surface temperature trends. *Geophysical Research Letters* 45(2):1086–1097.

Kramarova N, Newman PA, Nash ER, Strahan SE, Long CS, Johnson B, Pitts M, Santee ML, Petropavlovskikh I, Coy L & de Laat J (2020). 2019 Antarctic ozone hole (in 'State of the climate in 2019'). *Bulletin of the American Meteorological Society* 101(8):S310–S312.

Krause DJ, Goebel ME & Kurle CM (2020). Leopard seal diets in a rapidly warming polar region vary by year, season, sex, and body size. *BMC Ecology* 20:32.

Krüger L, Huerta MF, Santa Cruz F & Cárdenas CA (2021). Antarctic krill fishery effects over penguin populations under adverse climate conditions: implications for the management of fishing practices. *Ambio* 50(3):560–571.

Kudinova AG, Lysak LV, Soina VS, Mergelov NS, Dolgikh AV & Shorkunov IG (2015). Bacterial communities in the soils of cryptogamic barrens of East Antarctica (the Larsemann Hills and Thala Hills oases). *Eurasian Soil Science* 48(3):276–287.

Kühn S, van Oyen A, Bravo Rebolledo EL, Ask AV & van Franeker JA (2021). Polymer types ingested by northern fulmars (*Fulmarus glacialis*) and Southern Hemisphere relatives. *Environmental Science and Pollution Research* 28:1643–1655.

Kumar V, Shahi SK & Singh S (2018). Bioremediation: an eco-sustainable approach for restoration of contaminated sites. In: Singh J, Sharma D, Kumar G & Sharma NR (eds), *Microbial bioprospecting for sustainable development*, Springer, Singapore, 115–136.

Kusahara K, Williams GD, Massom R, Reid P & Hasumi H (2019). Spatiotemporal dependence of Antarctic sea ice variability to dynamic and thermodynamic forcing: a coupled ocean–sea ice model study. *Climate Dynamics* 52(7–8):3791–3807.

Labrousse S, Sallée JB, Fraser AD, Massom RA, Reid P, Sumner M, Guinet C, Harcourt R, McMahon CR, Bailleul F, Hindell MA & Charrassin JB (2017). Under the sea ice: exploring the relationship between sea ice and the foraging behaviour of southern elephant seals in East Antarctica. *Progress in Oceanography* 156:17–40.

Lambrechts S, Willems A & Tahon G (2019). Uncovering the uncultivated majority in Antarctic soils: toward a synergistic approach. *Frontiers in Microbiology* 10:242.

Larour E, Seroussi H, Adhikari S, Ivins E, Caron L, Morlighem M & Schlegel N (2019). Slowdown in Antarctic mass loss from solid Earth and sea-level feedbacks. *Science* 364(6444):eaav7908.

Lauro FM, DeMaere MZ, Yau S, Brown MV, Ng C, Wilkins D, Raftery MJ, Gibson JAE, Andrews-Pfannkoch C, Lewis M, Hoffman JM, Thomas T & Cavicchioli R (2011). An integrative study of a meromictic lake ecosystem in Antarctica. *ISME Journal* 5(5):879–895.

Lavery TJ, Roudnew B, Seymour J, Mitchell JG, Smetacek V & Nicol S (2014). Whales sustain fisheries: blue whales stimulate primary production in the Southern Ocean. *Marine Mammal Science* 30(3):888–904.

Lazer E & McGowan A (1990). *Heard Island archaeological survey (1986–1987)*, Department of Architectural and Design Science, University of Sydney.

Lazer E (2006). *Antarctic and sub-Antarctic cultural heritage*, Australian Government Department of Environment and Heritage, Canberra.

Leaper R, Cooke J, Trathan P, Reid K, Rowntree V & Payne R (2006). Global climate drives southern right whale (*Eubalaena australis*) population dynamics. *Biology Letters* 2(2):289–292.

Leaper R, Best PB, Branch TA, Donovan GP, Murase H & Van Waerebeek K (2008). *Report of review group of data sources on odontocetes in the Southern Ocean in preparation for IWC/CCAMLR workshop in August 2008*, report no. CCAMLR-IWC-WS-08/05, Commission for the Conservation of Antarctic Marine Living Resources, Hobart.

Learmonth JA, MacLeod CD, Santos MB, Pierce GJ, Crick HQP & Robinson RA (2006). Potential effects of climate change on marine mammals. *Oceanography and Marine Biology: An Annual Review* 44:431–464.

Lee JR, Raymond B, Bracegirdle TJ, Chadès I, Fuller RA, Shaw JD & Terauds A (2017). Climate change drives expansion of Antarctic ice-free habitat. *Nature* 547(7661):49–54.

Leihy RI, Coetzee BWT, Morgan F, Raymond B, Shaw JD, Terauds A, Bastmeijer K & Chown SL (2020). Antarctica's wilderness fails to capture continent's biodiversity. *Nature* 583(7817):567–571.

Lewis PJ, McGrath TJ, Emmerson L, Allinson G & Shimeta J (2020). Adélie penguin colonies as indicators of brominated flame retardants (BFRs) in East Antarctica. *Chemosphere* 250:126320.

Lewis PN, Hewitt CL, Riddle M & McMinn A (2003). Marine introductions in the Southern Ocean: an unrecognised hazard to biodiversity. *Marine Pollution Bulletin* 46(2):213–223.

Lewis Smith RI (1999). Biological and environmental characteristics of three cosmopolitan mosses dominant in continental Antarctica. *Journal of Vegetation Science* 10(2):231–242.

Li Q, Lee S, England MH & McClean JL (2019). Seasonal-to-interannual response of Southern Ocean mixed layer depth to the southern annular mode from a global 1/10° ocean model. *Journal of Climate* 32(18):6177–6195.

Liggett D, Frame B, Gilbert N & Morgan F (2017). Is it all going south? Four future scenarios for Antarctica. *Polar Record* 53(5):459–478.

Lim EP, Hendon HH, Boschat G, Hudson D, Thompson DWJ, Dowdy AJ & Arblaster JM (2019). Australian hot and dry extremes induced by weakenings of the stratospheric polar vortex. *Nature Geoscience* 12(11):896–901.

Lim EP, Hendon HH, Buttler AH, Garreaud RD, Polichtchouk I, Shepherd TG, Scaife A, Comer R, Coy L, Newman PA, Thompson DWJ & Nakamura H (2020). The 2019 Antarctic sudden stratospheric warming. *Stratosphere–Troposphere Processes and their Role in Climate Newsletter* 54:10–13.

Lohan D & Johnston S (2003). *The international regime for bioprospecting: existing policies and emerging issues for Antarctica*, United Nations University Institute of Advanced Studies, Tokyo.

Lucieer A, Bender A & Harris U (2009). *Remote sensing HIMI project 2008/2009: final report*, Australian Antarctic Division Data Centre, Kingston, Tasmania.

Łukowski AB (1983). DDT residues in the tissues and eggs of three species of penguins from breeding colonies at Admiralty Bay (King George Island, South Shetland Islands). *Polish Polar Research* 4(1–4):129–134.

Lüthi D, Le Floch M, Bereiter B, Blunier T, Barnola JM, Siegenthaler U, Raynaud D, Jouzel J, Fischer H, Kawamura K & Stocker TF (2008). High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* 453(7193):379–382.

Ma X (2020). An economic and legal analysis of trade measures against illegal, unreported and unregulated fishing. *Marine Policy* 117:103980.

Macdonald JA, Barton KJ & Metcalf P (2002). Chinstrap penguins (*Pygoscelis antarctica*) nesting on Sabrina Islet, Balleny Islands, Antarctica. *Polar Biology* 25(6):442–447.

MacFarling Meure C, Etheridge D, Trudinger C, Steele P, Langenfelds R, van Ommen T, Smith A & Elkins J (2006). Law Dome CO_2, CH_4 and N_2O ice core records extended to 2000 years BP. *Geophysical Research Letters* 33(14):L14810.

Mackay D & Wania F (1995). Transport of contaminants to the Arctic: partitioning, processes and models. *Science of the Total Environment* 160–161:25–38.

March-Salas M & Pertierra LR (2020). Warmer and less variable temperatures favour an accelerated plant phenology of two invasive weeds across sub-Antarctic Macquarie Island. *Austral Ecology* 45(5):572–585.

Marshall GJ (2003). Trends in the Southern Annular Mode from observations and reanalyses. *Journal of Climate* 16(24):4134–4143.

Marshall GJ (2007). Half-century seasonal relationships between the Southern Annular Mode and Antarctic temperatures. *International Journal of Climatology* 27(3):373–383.

Martin-Español A, Bamber JL & Zammit-Mangion A (2017). Constraining the mass balance of East Antarctica. *Geophysical Research Letters* 44(9):4168–4175.

Martorell MM, Ruberto LAM, de Figueroa LIC & Mac Cormack WP (2019). Antarctic yeasts as a source of enzymes for biotechnological applications. In: Rosa L (ed), *Fungi of Antarctica*, Springer, Cham, Switzerland, 285–304.

Maschette D & Welsford DC (2019). Population dynamics and life-history plasticity of mackerel icefish (*Champsocephalus gunnari*) within the vicinity of Heard Island and the McDonald Islands. In: Welsford D, Dell J & Duhamel G (eds), *The Kerguelen Plateau: marine ecosystem and fisheries*, Australian Antarctic Division, Kingston, Tasmania, 255–258.

Massom RA & Stammerjohn SE (2010). Antarctic sea ice change and variability: physical and ecological implications. *Polar Science* 4(2):149–186.

Massom RA, Giles AB, Fricker HA, Warner RC, Legresy B, Hyland G, Young N & Fraser AD (2010). Examining the interaction between multi-year landfast sea ice and the Mertz Glacier Tongue, East Antarctica: another factor in ice sheet stability? *Journal of Geophysical Research: Ocean* 115(C12):C12027.

Massom RA, Reid P, Raymond B, Stammerjohn S, Fraser AD & Ushio S (2013). Change and variability in East Antarctic sea ice seasonality, 1979/80–2009/10. *PLOS ONE* 8(5):e64756.

Massom RA, Scambos TA, Bennetts LG, Reid P, Squire VA & Stammerjohn SE (2018). Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. *Nature* 558(7710):383–389.

Matear RJ, O'Kane TJ, Risbey JS & Chamberlain M (2015). Sources of heterogeneous variability and trends in Antarctic sea-ice. *Nature Communications* 6:8656.

Mattlin RH & Cawthorn MW (1986). Marine debris: an international problem. *New Zealand Environment* 51:3–6.

McInnes J, Bird J, Deagle B, Alderman R & Shaw J (2019). *Detecting cryptic burrowing petrels recovery post eradication in a remote landscape*, National Environmental Science Programme Threatened Species Recovery Hub Project 4.2.3.4, Threatened Species Recovery Hub, Brisbane.

McInnes JC, Jarman SN, Lea MA, Raymond B, Deagle BE, Phillips RA, Catry P, Stanworth A, Weimerskirch H, Kusch A, Gras M, Cherel Y, Maschette D & Alderman R (2017). DNA metabarcoding as a marine conservation and management tool: a circumpolar examination of fishery discards in the diet of threatened albatrosses. *Frontiers in Marine Science* 4:277.

McInnes JC, Bird JP, Deagle BE, Polanowski AM & Shaw JD (2021). Using DNA metabarcoding to detect burrowing seabirds in a remote landscape. *Conservation Science and Practice* 3(7):e439.

McLandress C, Shepherd TG, Scinocca JF, Plummer DA, Sigmond M, Jonsson AI & Reader MC (2011). Separating the dynamical effects of climate change and ozone depletion. Part II: Southern Hemisphere troposphere. *Journal of Climate* 24(6):1850–1868.

McWatters RS, Wilkins D, Spedding T, Hince G, Raymond B, Lagerewskij G, Terry D, Wise L & Snape I (2016a). On site remediation of a fuel spill and soil reuse in Antarctica. *Science of the Total Environment* 571:963-973.

McWatters RS, Wilkins D, Spedding T, Hince G, Raymond B, Lagerewskij G, Terry D, Wise L & Snape I (2016b). On site remediation of a fuel spill and soil reuse in Antarctica. *Science of the Total Environment* 571:963–973.

Meehl GA, Arblaster JM, Chung CTY, Holland MM, DuVivier A, Thompson L, Yang D & Bitz CM (2019). Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. *Nature Communications* 10:14.

Mengel M & Levermann A (2014). Ice plug prevents irreversible discharge from East Antarctica. *Nature Climate Change* 4(6):451–455.

Menzel ME & Merlis TM (2019). Connecting direct effects of CO_2 radiative forcing to ocean heat uptake and circulation. *Journal of Advances in Modeling Earth Systems* 11(7):2163–2176.

Meredith M, Sommerkorn M, Cassotta S, Derksen C, Ekaykin A, Hollowed A, Kofinas G, Mackintosh A, Melbourne-Thomas J, Muelbert MMC, Ottersen G, Pritchard H & Schurr EAG (in press). Polar regions. In: Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B & Weyer NM (eds), *IPCC special report on the ocean and cryosphere in a changing climate*, Intergovernmental Panel on Climate Change, Switzerland.

Mergelov N, Dolgikh A, Shorkunov I, Zazovskaya E, Soina V, Yakushev A, Fedorov-Davydov D, Pryakhin S & Dobryansky A (2020). Hypolithic communities shape soils and organic matter reservoirs in the ice-free landscapes of East Antarctica. *Scientific Reports* 10:10277.

Mergelov NS (2014). Soils of wet valleys in the Larsemann Hills and Vestfold Hills oases (Princess Elizabeth Land, East Antarctica). *Eurasian Soil Science* 47(9):845–862.

Metchava R, Beltcheva M, Kalinova G, Marinova M, Rojas JAH & Peneva V (2017). Organochlorine pesticides in feathers of penguins of the family Pygoscelidae from Livingston and Peterman Islands, Western Antarctica. *Acta Zoologica Bulgarica* (Suppl 8):183–188.

Meyer B, Atkinson A, Bernard KS, Brierley AS, Driscoll R, Hill SL et al. (2020). Successful ecosystem-based management of Antarctic krill should address uncertainties in krill recruitment, behaviour and ecological adaptation. *Communications Earth and Environment* 1:28.

MFAT (New Zealand Ministry of Foreign Affairs and Trade) (n.d.). Ross Sea region marine protected area, MFAT, Wellington, accessed 12 May 2021, https://www.mfat.govt.nz/en/environment/antarctica-and-the-southern-ocean/ross-sea-region-marine-protected-area/.

Miller DE & Agnew D (2000). Management of krill fisheries in the Southern Ocean. In: Everson I (ed), *Krill: biology, ecology and fisheries*, Blackwell Science, Oxford, United Kingdom, 300–337.

Mintenbeck K, Barrera-Oro ER, Brey T, Jacob U, Knust R, Mark FC, Moreira E, Strobel A & Arntz WE (2012). Impact of climate change on fishes in complex Antarctic ecosystems. *Advances in Ecological Research* 46:351–426.

Mintenbeck K & Torres JJ (2017). Impact of climate change on the Antarctic silverfish and its consequences for the Antarctic ecosystem. In: Vacchi M, Pisano E & Ghigliotti L (eds), *Advances in polar ecology,* vol. 3, *The Antarctic silverfish: a keystone species in a changing ecosystem*, Springer, Cham, Switzerland, 253–286.

Misiak M, Goodall-Copestake WP, Sparks TH, Worland MR, Boddy L, Magan N, Convey P, Hopkins DW & Newsham KK (2021). Inhibitory effects of climate change on the growth and extracellular enzyme activities of a widespread Antarctic soil fungus. *Global Change Biology* 27(5):1111–1125.

Mooney T, Wasley J, Raymond B, Andrew N & King C (2019). Response of the Native Springtail Parisotoma insularis to Diesel Fuel-Contaminated Soils Under Field-Realistic Exposure Conditions at Subantarctic Macquarie Island. *Integrated Environmental Assessment and Management* 15.

Morgenstern O (2021). The Southern Annular Mode in 6th coupled model intercomparison project models. *Journal of Geophysical Research: Atmospheres* 126(5):e2020JD034161.

Morin PA, Archer FI, Foote AD, Vilstrup J, Allen EE, Wade P et al. (2010). Complete mitochondrial genome phylogeographic analysis of killer whales (*Orcinus orca*) indicates multiple species. *Genome Research* 20(7):908–916.

Morlighem M, Rignot E, Binder T, Blankenship D, Drews R, Eagles G et al. (2020). Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nature Geoscience* 13(2):132–137.

Nash SMB (2018). Toxicological risks and considerations associated with lipophilic contaminant burdens of Southern Ocean mysticetes. In: Fossi MC & Panti C (eds), *Marine mammal ecotoxicology: impacts of multiple stressors on population health*, Academic Press, Cambridge, Massachusetts, 381–400.

National Academies of Sciences, Engineering, and Medicine (2017). *Antarctic sea ice variability in the Southern Ocean-climate system: proceedings of a workshop*, National Academies Press, Washington, 1–36.

Navarro JM, Paschke K, Ortiz A, Vargas-Chacoff L, Pardo LM & Valdivia N (2019). The Antarctic fish *Harpagifer antarcticus* under current temperatures and salinities and future scenarios of climate change. *Progress in Oceanography* 174:37–43.

Neale RE, Barnes PW, Robson TM, Neale PJ, Williamson CE, Zepp RG et al. (2021). Environmental effects of stratospheric ozone depletion, UV radiation, and interactions with climate change: UNEP environmental effects assessment panel, update 2020. *Photochemical and Photobiological Sciences* 20:1–67.

Negoita TG, Covaci A, Gheorghe A & Schepens P (2003). Distribution of polychlorinated biphenyls (PCBs) and organochlorine pesticides in soils from the East Antarctic coast. *Journal of Environmental Monitoring* 5(2):281–286.

Nevitt GA (2000). Olfactory foraging by Antarctic procellariiform seabirds: life at high Reynolds numbers. *Biological Bulletin* 198(2):245–253.

Nevitt GA (2008). Sensory ecology on the high seas: the odor world of the procellariiform seabirds. *Journal of Experimental Biology* 211(11):1706–1713.

Newman L, Heil P, Trebilco R, Katsumata K, Constable A, van Wijk E et al. (2019). Delivering sustained, coordinated, and integrated observations of the Southern Ocean for global impact. *Frontiers in Marine Science* 6:433.

Newsham KK & Robinson SA (2009). Responses of plants in polar regions to UVB exposure: a meta-analysis. *Global Change Biology* 15(11):2574–2589.

Newsham KK, Davey ML, Hopkins DW & Dennis PG (2021). Regional diversity of maritime Antarctic soil fungi and predicted responses of guilds and growth forms to climate change. *Frontiers in Microbiology* 11:615659.

Nicol S, Foster JL & Kawaguchi S (2012). The fishery for Antarctic krill: recent developments. *Fish and Fisheries* 13(1):30–40.

Nicol S & Foster J (2016). The fishery for Antarctic krill: its current status and management regime. In: Siegel V (ed), *Advances in polar ecology, Biology and ecology of Antarctic krill*, Springer, Cham, Switzerland, 387–421.

Nicolas JP & Bromwich DH (2014). New reconstruction of Antarctic near-surface temperatures: multidecadal trends and reliability of global reanalyses. *Journal of Climate* 27(21):8070–8093.

Nicolas JP, Vogelmann AM, Scott RC, Wilson AB, Cadeddu MP, Bromwich DH, Verlinde J, Lubin D, Russell LM, Jenkinson C, Powers HH, Ryczek M, Stone G & Wille JD (2017). January 2016 extensive summer melt in West Antarctica favoured by strong El Niño. *Nature Communications* 8:15799.

Nielsen UF, Wall DH, Adams BJ & Virginia RA (2011). Antarctic nematode communities: observed and predicted responses to climate change. *Polar Biology* 34:1701–1711.

Nielsen UN & Wall DH (2013). The future of soil invertebrate communities in polar regions: different climate change responses in the Arctic and Antarctic? *Ecology Letters* 16:409–419.

NOAA (National Oceanic and Atmospheric Administration) (2021). Trends in atmospheric carbon dioxide (dataset), NOAA, Washington, https://www.esrl.noaa.gov/gmd/ccgg/trends/.

Noble TL, Rohling EJ, Aitken ARA, Bostock HC, Chase Z, Gomez N et al. (2020). The sensitivity of the Antarctic ice sheet to a changing climate: past, present, and future. *Reviews of Geophysics* 58(4):e2019RG000663.

Notz D & Bitz CM (2017). Sea ice in Earth system models. In: Thomas DN (ed), *Sea ice*, 3rd edn, John Wiley & Sons, Hoboken, New Jersey, 304–325.

Nydahl AC, King CK, Wasley J, Jolley DF & Robinson SA (2015). Toxicity of fuel-contaminated soil to Antarctic moss and terrestrial algae. *Environmental Toxicology & Chemistry* 34:2004–2012.

O'Connor SE (ed) (2016). *Methods in enzymology*, vol. 576, *Synthetic biology and metabolic engineering in plants and microbes part B: metabolism in plants*, Academic Press, Oxford, United Kingdom.

O'Neill TA, Balks MR & López-Martínez J (2013). Visual recovery of desert pavement surfaces following impacts from vehicle and foot traffic in the Ross Sea region of Antarctica. *Antarctic Science* 25(4):514–530.

Ogaki MB, Vieira R, Muniz MC, Zani CL, Alves TMA, Policarpo AS, Murta SMF, Barbosa EC, Oliveira JG, Ceravolo IP, Pereira PO, Rosa CA & Rosa LH (2020a). Diversity, ecology, and bioprospecting of culturable fungi in lakes impacted by anthropogenic activities in maritime Antarctica. *Extremophiles* 24(4):637–655.

Ogaki MB, Coelho LC, Vieira R, Neto AA, Zani CL, Alves TMA et al. (2020b). Cultivable fungi present in deep-sea sediments of Antarctica: taxonomy, diversity, and bioprospecting of bioactive compounds. *Extremophiles* 24(2):227–238.

Oliver ECJ, Donat MG, Burrows MT, Moore PJ, Smale DA, Alexander LV et al. (2018). Longer and more frequent marine heatwaves over the past century. *Nature Communications* 9:1324.

Oliver ECJ, Burrows MT, Donat MG, Sen Gupta A, Alexander LV, Perkins-Kirkpatrick SE, Benthuysen JA, Hobday AJ, Holbrook NJ, Moore PJ, Thomsen MS, Wernberg T & Smale DA (2019). Projected marine heatwaves in the 21st century and the potential for ecological impact. *Frontiers in Marine Science* 6:734.

Orr JC, Caldeira K, Fabry V, Gattuso JP, Haugan P, Lehodey P, Patoja S, Pörtner HO, Riebesell U, Trull T, Urban E, Hood M & Broadgate W (2009). Research priorities for understanding ocean acidification. *Oceanography* 22(4):182–189.

Owens I & Zawar-Reza P (2015). Weather and climate. In: Liggett D, Storey B, Cook Y & Meduna V (eds), *Exploring the last continent: an introduction to Antarctica*, Springer, Cham, Switzerland, 91–114.

Pacyna AD, Jakubas D, Ausems ANMA, Frankowski M, Polkowska Ż & Wojczulanis-Jakubas K (2019). Storm petrels as indicators of pelagic seabird exposure to chemical elements in the Antarctic marine ecosystem. *Science of the Total Environment* 692:382–392.

Park HJ, Yeon I, Han E, Lee YJ, Hanchet SM, Baeck GW, Kwon Y, Choi SG, Lee DW & Kang CK (2015). Diet study of Antarctic toothfish caught in the east Antarctic based on stomach content, fatty acid and stable isotope analyses. *CCAMLR Science* 22:29–44.

Parkinson CL (2019). A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. *Proceedings of the National Academy of Sciences* 116(29):14414–14423.

Parks and Wildlife Service Tasmania & DEST (Australian Government Department of the Environment, Sport and Territories) (1996). *Nomination of Macquarie Island by the Government of Australia for inscription on the World Heritage List*, DEST, Canberra.

Pascoe P, McInnes JC, Lashko A, Robinson S, Achurch H, Salton M, Alderman R & Carmichael N (2020). Trends in gentoo penguin (*Pygoscelis papua*) breeding population size at Macquarie Island. *Polar Biology* 43(7):877–886.

Pattyn F & Morlighem M (2020). The uncertain future of the Antarctic ice sheet. *Science* 367(6484):1331–1335.

Paul S, Hendricks S, Ricker R, Kern S & Rinne E (2018). Empirical parametrization of Envisat freeboard retrieval of Arctic and Antarctic sea ice based on CryoSat-2: progress in the ESA climate change initiative. *The Cryosphere* 12(7):2437–2460.

Pauly T, Nicol S, Higginbottom I, Hosie G & Kitchener J (2000). Distribution and abundance of Antarctic krill (*Euphausia superba*) off East Antarctica (80–150°E) during the Austral summer of 1995/1996. *Deep-Sea Research Part II: Topical Studies in Oceanography* 47(12–13):2465–2488.

Peck LS (2005). Prospects for survival in the Southern Ocean: vulnerability of benthic species to temperature change. *Antarctic Science* 17(4):497–507.

Peck VL, Oakes RL, Harper EM, Manno C & Tarling GA (2018). Pteropods counter mechanical damage and dissolution through extensive shell repair. *Nature Communications* 9:264.

Pecl GT, Araújo MB, Bell JD, Blanchard J, Bonebrake TC, Chen IC et al. (2017). Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* 355(6332):eaai9214.

Peeters K, Hodgson DA, Convey P & Willems A (2011). Culturable diversity of heterotrophic bacteria in Forlidas Pond (Pensacola Mountains) and Lundström Lake (Shackleton Range), Antarctica. *Microbial Ecology* 62(2):399–413.

Pellichero V, Sallée JB, Chapman CC & Downes SM (2018). The Southern Ocean meridional overturning in the sea-ice sector is driven by freshwater fluxes. *Nature Communications* 9:1789.

Pemberton D, Brothers NP & Kirkwood R (1992). Entanglement of Australian fur seals in man-made debris in Tasmanian waters. *Wildlife Research* 19(2):151–159.

Peng G, Meier WN, Scott DJ & Savoie MH (2013). A long-term and reproducible passive microwave sea ice concentration data record for climate studies and monitoring. *Earth System Science Data* 5(2):311–318.

Perera-Castro AV, Waterman MJ, Turnbull JD, Ashcroft MB, McKinley E, Watling JR, Bramley-Alves J, Casanova-Katny A, Zuniga G, Flexas J & Robinson SA (2020). It is hot in the sun: Antarctic mosses have high temperature optima for photosynthesis despite cold climate. *Frontiers in Plant Science* 11:1178.

Perold V, Schoombie S & Ryan PG (2020). Decadal changes in plastic litter regurgitated by albatrosses and giant petrels at sub-Antarctic Marion Island. *Marine Pollution Bulletin* 159:111471.

Péron C, Welsford DC, Ziegler P, Lamb TD, Gasco N, Chazeau C, Sinègre R & Duhamel G (2016). Modelling spatial distribution of Patagonian toothfish through life-stages and sex and its implications for the fishery on the Kerguelen Plateau. *Progress in Oceanography* 141:81–95.

Perovich D, Meier W, Tschudi M, Hendricks S, Petty AA, Divine D et al. (2020). Sea ice. In: Thoman RL, Richter-Menge J & Druckenmiller ML (eds), *Arctic report card 2020*, National Oceanic and Atmospheric Administration, Washington, 44–53.

Perren BB, Hodgson DA, Roberts SJ, Sime L, Van Nieuwenhuyze W, Verleyen E & Vyverman W (2020). Southward migration of the Southern Hemisphere westerly winds corresponds with warming climate over centennial timescales. *Communications Earth and Environment* 1:58.

Persistent Organic Pollutants Review Committee (2020). *Dechlorane Plus and its syn- and anti-isomers - draft risk profile*, POPRC IWGot (ed), Geneva.

Pertierra LR, Baker M, Howard C, Vega GC, Olalla-Tarrage MA & Scott J (2016). Assessing the invasive risk of two non-native *Agrostis* species on sub-Antarctic Macquarie Island. *Polar Biology* 39(12):2361–2371.

Petry MV & Benemann VRF (2017). Ingestion of marine debris by the white-chinned petrel (*Procellaria aequinoctialis*): is it increasing over time off southern Brazil? *Marine Pollution Bulletin* 117(1–2):131–135.

Phillips L, Janion-Scheepers C, Houghton M, Terauds A, Potapov M & Chown SL (2017). Range expansion of two invasive springtails on sub-Antarctic Macquarie Island. *Polar Biology* 40:2137–2142.

Pisitsak P, Tungsombatvisit N & Singhanu K (2018). Utilization of waste protein from Antarctic krill oil production and natural dye to impart durable UV-properties to cotton textiles. *Journal of Cleaner Production* 174:1215–1223.

Pitman RL & Ensor P (2003). Three forms of killer whales (*Orcinus orca*) in Antarctic waters. *Journal of Cetacean Research and Management* 5(2):131–139.

Pollard D, DeConto RM & Alley RB (2015). Potential Antarctic ice sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters* 412:112–121.

Polmear R, Stark JS, Roberts D & McMinn A (2015). The effects of oil pollution on Antarctic benthic diatom communities over 5 years. *Marine Pollution Bulletin* 90(1–2):33–40.

Polvani LM, Waugh DW, Correa GJP & Son SW (2011). Stratospheric ozone depletion: the main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere. *Journal of Climate* 24(3):795–812.

Porter DF, Springer SR, Padman L, Fricker HA, Tinto KJ, Riser SC, Bell RE & the ROSETTA-Ice Team (2019). Evolution of the seasonal surface mixed layer of the Ross Sea, Antarctica, observed with autonomous profiling floats. *Journal of Geophysical Research: Oceans* 124(7):4934–4953.

Pörtner HO, Peck LS & Somero G (2007). Thermal limits and adaptation in marine Antarctic ectotherms: an integrative view. *Philosophical Transactions of the Royal Society B* 362(1488):2233–2258.

Potts LJ, Gantz JD, Kawarasaki Y, Philip BN, Gonthier DJ, Law AD, Moe L, Unrine JM, McCulley RL, Lee REJ, Denlinger DL & Teets NM (2020). Environmental factors influencing fine-scale distribution of Antarctica's only endemic insect. *Oecologia* 194:529–539.

Powell SM, Stark JS, I. S, Woolfenden ENM, Bowman JP & Riddle MJ (2010). Effects of diesel and lubricant oils on Antarctic benthic microbial communities over five years. . *Aquatic Microbial Ecology* 61:119-127.

Prather HM, Casanova-Katny A, Clements AF, Chmielewski MW, Balkan MA, Shortlidge EE, Rosenstiel TN & Eppley SM (2019). Species-specific effects of passive warming in an Antarctic moss system. *Royal Society Open Science* 6(11):190744.

Pritchard HD, Ligtenberg SRM, Fricker HA, Vaughan DG, van den Broeke MR & Padman L (2012). Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature* 484(7395):502–505.

Pugh PJA & Convey P (2008). Surviving out in the cold: Antarctic endemic invertebrates and their refugia. *Journal of Biogeography* 35(12):2176–2186.

Rae JWB, Burke A, Robinson LF, Adkins JF, Chen T, Cole C, Greenop T, Li E, Littley EFM, Nita DC, Stewart JA & Taylor BJ (2018). CO_2 storage and release in the deep Southern Ocean on millennial to centennial timescales. *Nature* 562:569–573.

Rahaman W, Chatterjee S, Ejaz T & Thamban M (2019). Increased influence of ENSO on Antarctic temperature since the industrial era. *Scientific Reports* 9:6006.

Randel WJ, Polvani L, Wu F, Kinnison DE, Zou CZ & Mears C (2017). Troposphere-stratosphere temperature trends derived from satellite data compared with ensemble simulations from WACCM. *Journal of Geophysical Research: Atmospheres* 122(18):9651–9667.

Rapp HT, Janussen D & Tendal OS (2011). Calcareous sponges from abyssal and bathyl depths in the Weddell Sea, Antarctica. *Deep-Sea Research Part II: Topical Studies in Oceanography* 58(1–2):58–67.

Ray DK, West PC, Clark M, Gerber JS, Prishchepov AV & Chatterjee S (2019). Climate change has likely already affected global food production. *PLOS ONE* 14(5):e0217148.

Raymond T, King C, Raymond B, Stark J & Snape I (2017). Oil pollution in Antarctica. In: Fingas M (ed), *Oil spill science and technology*, 2nd edn, Gulf Professional Publishing, Houston, 759–803.

Reid K (2019). Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR): implementation of conservation of Southern Ocean marine living resources. In: Liu N, Brooks CM & Qin T (eds), *Governing marine living resources in the polar regions*, Edward Elgar Publishing, Cheltenham, United Kingdom, 30–42.

Reid P & Massom R (2015). Successive Antarctic sea ice extent records during 2012, 2013, and 2014 (in 'State of the climate in 2014'). *Bulletin of the American Meteorological Society* 96(7):S163–S164.

Reid P, Stammerjohn S, Massom RA, Lieser JL, Barreira S & Scambos T (2017). Sea ice extent, concentration, and seasonality (in 'State of the climate in 2016'). *Bulletin of the American Meteorological Society* 98(8):S163–S166.

Reid P, Stammerjohn S, Massom RA, Lieser J, Barreira S & Scambos T (2018). Sea ice extent, concentration, and seasonality (in 'State of the climate in 2017'). *Bulletin of the American Meteorological Society* 99(8):S183–S185.

Reid P, Stammerjohn S, Massom RA, Barreira S, Scambos T & Lieser JL (2020). Sea ice extent, concentration, and seasonality (in 'State of the climate in 2019'). *Bulletin of the American Meteorological Society* 101(8):S304–S306.

Revill AT, Snape I, Lucieer A & Guille D (2007). Constraints on transport and weathering of petroleum contamination at Casey Station, Antarctica. *Cold Regions Science and Technology* 48:154-167.

Rexer-Huber K, Veale AJ, Catry P, Cherel Y, Dutoit L, Foster Y et al. (2019). Genomics detects population structure within and between ocean basins in a circumpolar seabird: the white-chinned petrel. *Molecular Ecology* 28(20):4552–4572.

Rhein M, Rintoul SR, Aoki S, Campos E, Chambers D, Feely RA, Gulev S, Johnson GC, Josey SA, Kostianoy A, Mauritzen C, Roemmich D, Talley LD & Wang F (2013). Observations: ocean. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (eds), *Climate change 2013: the physical science basis*, Cambridge University Press, Cambridge, United Kingdom and New York, United States, 255–316.

Richard G, Bonnel J, Tixier P, Arnould JPY, Janc A & Guinet C (2020). Evidence of deep-sea interactions between toothed whales and longlines. *Ambio* 49(1):173–186.

Rignot E, Mouginot J, Morlighem M, Seroussi H & Scheuchl B (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters* 41(10):3502–3509.

Rignot E, Mouginot J, Scheuchl B, van den Broeke M, van Wessem MJ & Morlighem M (2019). Four decades of Antarctic ice sheet mass balance from 1979–2017. *Proceedings of the National Academy of Sciences* 116(4):1095–1103.

Rintoul SR, Hughes C & Olbers D (2001). The Antarctic circumpolar current system. In: Siedler G, Church J & Gould J (eds), *Ocean circulation and climate: observing and modelling the global ocean*, Academic Press, London, 271–302.

Rintoul SR (2007). Rapid freshening of Antarctic bottom water formed in the Indian and Pacific oceans. *Geophysical Research Letters* 34(6):L06606.

Rintoul SR (2018). The global influence of localized dynamics in the Southern Ocean. *Nature* 558(7709):209–218.

Rintoul SR, Chown SL, DeConto RM, England MH, Fricker HA, Masson-Delmotte V, Naish TR, Siegert MJ & Xavier JC (2018). Choosing the future of Antarctica. *Nature* 558(7709):233–241.

Roach LA, Dörr J, Holmes CR, Massonnet F, Blockley EW, Notz D, Rackow T, Raphael MN, O'Farrell SP, Bailey DA & Bitz CM (2020). Antarctic sea ice area in CMIP6. *Geophysical Research Letters* 47(9):e2019GL086729.

Roberts J, Plummer C, Vance T, van Ommen T, Moy A, Poynter S, Treverrow A, Curran M & George S (2015). A 2000-year annual record of snow accumulation rates for Law Dome, East Antarctica. *Climate of the Past* 11(5):697–707.

Roberts JL, Warner RC, Young D, Wright A, van Ommen TD, Blankenship DD, Siegert M, Young NW, Tabacco IE, Forieri A, Passerini A, Zirizzotti A & Frezzotti M (2011). Refined broad-scale sub-glacial morphology of Aurora Subglacial Basin, East Antarctica derived by an ice-dynamics-based interpolation scheme. *The Cryosphere* 5(3):551–560.

Robinson SA & Copson GR (2014). Eradication of cats (*Felis catus*) from subantarctic Macquarie Island. *Ecological Management and Restoration* 15(1):34–40.

Robinson SA, King DH, Bramley-Alves J, Waterman MJ, Ashcroft MB, Wasley J, Turnbull JD, Miller RE, Ryan-Colton E, Benny T, Mullany K, Clarke LJ, Barry LA & Hua Q (2018). Rapid change in East Antarctic terrestrial vegetation in response to regional drying. *Nature Climate Change* 8(10):879–884.

Robinson SA, Klekociuk AR, King DH, Pizarro Rojas M, Zúñiga GE & Bergstrom DM (2020). The 2019/2020 summer of Antarctic heatwaves. *Global Change Biology* 26(6):3178-3180.

Rochman CM, Browne MA, Underwood AJ, van Franeker JA, Thompson RC & Amaral-Zettler LA (2016). The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived. *Ecology* 97(2):302–312.

Roemmich D, Church J, Gilson J, Monselesan D, Sutton P & Wijffels S (2015). Unabated planetary warming and its ocean structure since 2006. *Nature Climate Change* 5:240–245.

Ropert-Coudert Y, Kato A, Meyer X, Pellé M, MacIntos AJJ, Angelier F, Chastel O, Widmann M, Arthur B, Raymond B & Raclot T (2015). A complete breeding failure in an Adélie penguin colony correlates with unusual and extreme environmental events. *Ecography* 38(2):111–113.

Rosa LH, Zani CL, Cantrell CL, Duke SO, Van Dijck P, Desideri A & Rosa CA (2019). Fungi in Antarctica: diversity, ecology, effects of climate change, and bioprospection for bioactive compounds. In: Rosa LH (ed), *Fungi of Antarctica: diversity, ecology and biotechnological applications*, Springer, Cham, Switzerland, 1–17.

Rubino M, Etheridge DM, Trudinger CM, Allison CE, Battle MO, Langenfelds RL, Steele LP, Curran M, Bender M, White JWC, Jenk TM, Blunier T & Francey RJ (2013). A revised 1000 year atmospheric $\delta^{13}C$-CO_2 record from Law Dome and South Pole, Antarctica. *Journal of Geophysical Research: Atmospheres* 118(15):8482–8499.

Ruddell A (2006). An inventory of present glaciers on Heard Island and their historical variation. In: Green K & Woehler E (eds), *Heard Island: Southern Ocean sentinel*, Surrey, Beatty and Sons, Chipping Norton, New South Wales, 28–51.

Russell A, Gohlan M, Smedley A & Densham M (2015). The ultraviolet radiation environment during an expedition across the Drake Passage and on the Antarctic Peninsula. *Antarctic Science* 27(3):307–316.

Sallée JB (2018). Southern Ocean warming. *Oceanography* 31(2):52–62.

Salton M, Kliska K, Carmichael N & Alderman R (2019). Population status of the endemic royal penguin (*Eudyptes schlegeli*) at Macquarie Island. *Polar Biology* 42(4):771–781.

Samuels T, Rynearson TA & Collins S (2021). Surviving heatwaves: thermal experience predicts life and death in a Southern Ocean diatom. *Frontiers in Marine Science* 8:600343.

Sancho LG, Pintado A & Allan Green TG (2019). Antarctic studies show lichens to be excellent biomonitors of climate change. *Diversity* 11(3):42.

Scambos T, Hulbe C & Fahnestock M (2003). Climate-induced ice shelf disintegration in the Antarctic Peninsula. In: Domack E, Levente A, Burnet A, Bindschadler R, Convey P & Kirby M (eds), *Antarctic research series,* vol. 79, *Antarctic Peninsula climate variability: historical and paleoenvironmental perspectives*, American Geophysical Union, Washington, 79–92.

Scheffer VB (1958). *Seals, sea lions, and walruses: a review of the Pinnipedia*, Stanford University Press, Stanford, California.

Schlosser E, Haumann FA & Raphael MN (2018). Atmospheric influences on the anomalous 2016 Antarctic sea ice decay. *The Cryosphere* 12(3):1103–1119.

Schmidt AE & Ballard G (2020). Significant chick loss after early fast ice breakup at a high-latitude emperor penguin colony. *Antarctic Science* 32(3):180–185.

Schoof C (2007). Ice sheet grounding line dynamics: steady states, stability, and hysteresis. *Journal of Geophysical Research: Earth Surface* 112(F3): F03S28.

Schröder H, Janipour N, Müller WEG, Di Bella B, Bonaventura R, Russo R & Matranga V (2005). DNA damage and developmental defects after exposure to UV and heavy metals in sea urchin cells and embryos compared to other invertebrates. In: Matranga V (ed), *Progress in molecular and subcellular biology (marine molecular biotechnology),* vol. 39, *Echinodermata*, Springer, Berlin, 111–137.

Scott JJ & Kirkpatrick JB (2008). Rabbits, landslips and vegetation change on the coastal slopes of subantarctic Macquarie Island, 1980–2007: implications for management. *Polar Biology* 31(4):409–419.

Secretariat of the Antarctic Treaty (2006). *Practical guidelines for ballast water exchange in the Antarctic treaty area*, annex to resolution 3, Secretariat of the Antarctic Treaty, Buenos Aires.

Secretariat of the Antarctic Treaty (2021). The Antarctic Treaty, Secretariat of the Antarctic Treaty, Buenos Aires, accessed 4 May 2021, http://www.ats.aq/e/antarctictreaty.html.

Seibel BA, Maas AE & Dierssen HM (2012). Energetic plasticity underlies a variable response to ocean acidification in the pteropod, *Limacina helicina antarctica*. *PLOS ONE* 7(4):e30464.

Selkirk PM, Seppelt RD & Selkirk DR (1990). *Subantarctic Macquarie Island: environment and biology*, Cambridge University Press, Cambridge, United Kingdom.

Sen Gupta A, Thomsen M, Benthuysen JA, Hobday AJ, Oliver E, Alexander LV et al. (2020). Drivers and impacts of the most extreme marine heatwave events. *Scientific Reports* 10:19359.

Seyboth E, Groch KR, Dalla Rosa L, Reid K, Flores PAC & Secchi ER (2016). Southern right whale (*Eubalaena australis*) reproductive success is influenced by krill (*Euphausia superba*) density and climate. *Scientific Reports* 6:28205.

Shabangu FW, Andrew RK, Yemane D & Findlay KP (2020). Acoustic seasonality, behaviour and detection ranges of Antarctic blue and fin whales under different sea ice conditions off Antarctica. *Endangered Species Research* 43:21–37.

Singh J, Singh RP & Khare R (2018). Influence of climate change on Antarctic flora. *Polar Science* 18:94–101.

Sjöling S & Cowan DA (2000). Detecting human bacterial contamination in Antarctic soils. *Polar Biology* 23(9):644–650.

Skotnicki ML, Copson GR, Doube J, Gadd L, Selkirk-Bell JM & Selkirk PM (2009). Biology and population studies of two endemic *Nematoceras* (orchid) species on sub-Antarctic Macquarie Island. *Papers and Proceedings of the Royal Society of Tasmania* 143(2):61–71.

Smith B, Fricker HA, Gardner AS, Medley B, Nilsson J, Paolo FS et al. (2020). Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. *Science* 368(6496):1239–1242.

Smith KL & Polvani LM (2017). Spatial patterns of recent Antarctic surface temperature trends and the importance of natural variability: lessons from multiple reconstructions and the CMIP5 models. *Climate Dynamics* 48(7):2653–2670.

Solomon S, Daniel JS, Sanford TJ, Murphy DM, Plattner GK, Knutti R & Friedlingstein P (2010). Persistence of climate changes due to a range of greenhouse gases. *Proceedings of the National Academy of Sciences* 107(43):18354–18359.

Solomon S, Kinnison D, Bandoro J & Garcia R (2015). Simulation of polar ozone depletion: an update. *Journal of Geophysical Research: Atmospheres* 120(15):7958–7974.

Solomon S, Ivy D, Gupta M, Bandoro J, Santer B, Fu Q, Lin P, Garcia RR, Kinnison D & Mills M (2017). Mirrored changes in Antarctic ozone and stratospheric temperature in the late 20th versus early 21st centuries. *Journal of Geophysical Research: Atmospheres* 122(16):8940–8950.

Southwell C, Bengston J, Bester MN, Blix AS, Bornemann H, Boveng P et al. (2012). A review of data on abundance, trends in abundance, habitat use and diet of ice-breeding seals in the Southern Ocean. *CCAMLR Science* 19:49–74.

Southwell C, Emmerson L, Newbery K, McKinlay J, Kerry K, Woehler E & Ensor P (2015a). Re-constructing historical Adélie penguin abundance estimates by retrospectively accounting for detection bias. *PLOS ONE* 10(4):e0123540.

Southwell C, Emmerson L, McKinlay J, Newbery K, Takahashi A, Kato A, Barbraud C, DeLord K & Weimerskirch H (2015b). Spatially extensive standardized surveys reveal widespread, multi-decadal increase in East Antarctic Adélie penguin populations. *PLOS ONE* 10(10):e0139877.

Southwell C & Emmerson L (2019). Constraint in the midst of growth: decadal-scale Adélie penguin (*Pygoscelis adeliae*) population change at Scullin and Murray monoliths diverges from widespread increases across East Antarctica. *Polar Biology* 42(7):1397–1403.

Souza JS, Padilha JA, Pessoa ARL, Ivar do Sol JA, Alves MAS, Lobo-Hajdu G, Malm O, Costa ES & Torres JPM (2020). Trace elements in feathers of Cape petrel (*Daption capense*) from Antarctica. *Polar Biology* 43(7):911–917.

Springer K & Carmichael N (2012). Non-target species management for the Macquarie Island pest eradication project. In: Timm RM (ed), *Proceedings of the 25th Vertebrate Pest Conference*, Monterey, California, 5–8 March 2012, University of California, Davis, 38–47.

Springer K (2018). Eradication of invasive species on Macquarie Island to restore the natural ecosystem. In: Garnett S, Latch P, Lindenmayer D & Woinarski J (eds), *Recovering Australian threatened species: a book of hope*, CSIRO Publishing, Melbourne, 13–22.

SSC (Secretariat of the Stockholm Convention) (2020). *Stockholm Convention on Persistent Organic Pollutants (POPs)*, 2019 revision, SSC, Switzerland.

Stammerjohn S, Massom R, Rind D & Martinson D (2012). Regions of rapid sea ice change: an inter-hemispheric seasonal comparison. *Geophysical Research Letters* 39(6):L06501.

Stammerjohn S & Maksym T (2017). Gaining (and losing) Antarctic sea ice: variability, trends and mechanisms. In: Thomas DN (ed), *Sea ice*, 3rd edn, John Wiley & Sons, Hoboken, New Jersey, 261–289.

Staniland IJ, Ratcliffe N, Trathan PN & Forcada J (2018). Long term movements and activity patterns of an Antarctic marine apex predator: the leopard seal. *PLOS ONE* 13(6):e0197767.

Stark JS, Bridgen P, Dunshea G, Galton-Fenzi B, Hunter J, Johnstone G, King C, Leeming R, Palmer A, Smith J, Snape I, Stark S & Riddle M (2016). Dispersal and dilution of wastewater from an ocean outfall at Davis Station, Antarctica, and resulting environmental contamination. *Chemosphere* 152:142–157.

Steig EJ, Schneider DP, Rutherford SD, Mann ME, Comiso JC & Shindell DT (2009). Warming of the Antarctic ice-sheet surface since the 1957 international geophysical year. *Nature* 457(7228):459–462.

Stevens C, Hulbe C, Brewer M, Stewart C, Robinson N, Ohneiser C & Jendersie S (2020). Ocean mixing and heat transport processes observed under the Ross Ice Shelf control its basal melting. *Proceedings of the National Academy of Sciences* 117(29):16799–16804.

Stuecker MF, Bitz CM & Armour KC (2017). Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season. *Geophysical Research Letters* 44(17):9008–9019.

Su Z, Pilo GS, Corney S, Holbrook NJ, Mori M & Ziegler P (2021). Characterizing marine heatwaves in the Kerguelen Plateau region. *Frontiers in Marine Science* 7:531297.

Summerson R & Bishop ID (2012). The impact of human activities on wilderness and aesthetic values in Antarctica. *Polar Research* 31(1):10858.

Swan J (2018). IUU fishing and measures to improve enforcement and compliance. In: Werle D, Boudreau PR, Brooks MR, Butler MJA, Charles A, Coffen-Smout S, Griffiths D, McAllister I, McConnell ML, Porter I, Rolston SJ, Wells PG & International Ocean Institute – Canada (eds), *The future of ocean governance and capacity development*, Koninklijke Brill NV, Leiden, The Netherlands, 354–360.

Swart NC, Gille ST, Fyfe JC & Gillett NP (2018). Recent Southern Ocean warming and freshening driven by greenhouse gas emissions and ozone depletion. *Nature Geoscience* 11(11):836–841.

Takashima M, Shirai F, Sageshima M, Ikeda N, Okamoto Y & Dohi Y (2004). Distinctive bacteria-binding property of cloth materials. *American Journal of Infection Control* 32(1):27–30.

Tamsitt V, Drake HF, Morrison AK, Talley LD, Dufour CO, Gray AR, Griffies SM, Mazloff MR, Sarmiento JL, Wang J & Weijer W (2017). Spiraling pathways of global deep waters to the surface of the Southern Ocean. *Nature Communications* 8:172.

Taniguchi S, Colabuono FI, Dalla Rosa L, Secci ER, da Silva J, Maia DA & Montone RC (2019). Persistent organic pollutants in blubber of fin whales (*Balaenoptera physalus*) from the Southern Ocean. *Marine Pollution Bulletin* 145:148–152.

Tartu S, Angelier F, Wingfield JC, Bustamante P, Labadie P, Budzinski H, Weimerskirch H, Bustnes JO & Chastel O (2015). Corticosterone, prolactin and egg neglect behavior in relation to mercury and legacy POPs in a long-lived Antarctic bird. *Science of the Total Environment* 505:180–188.

Tasmania Parks and Wildlife Service (2020). *2020–21 criteria for the selection of commercial educational tourist visits to Macquarie Island*, Tasmania Parks and Wildlife Service, Hobart.

Tejedo P, Pertierra LR & Benayas J (2014). Trampling the Antarctic: consequences of pedestrian traffic on Antarctic soils. In: Tin T, Liggett D, Maher PT & Lamers M (eds), *Antarctic futures: human engagement with the Antarctic environment*, Springer, The Netherlands, 139–161.

Terauds A, Chown SL & Bergstrom DM (2011). Spatial scale and species identity influence the indigenous–alien diversity relationship in springtails. *Ecology* 92(7):1436–1447.

Terauds A, Chown SL, Morgan F, Peat HJ, Watts DJ, Keys H, Convey P & Bergstrom DM (2012). Conservation biogeography of the Antarctic. *Diversity and Distributions* 18(7):726–741.

Terauds A & Lee JR (2016). Antarctic biogeography revisited: updating the Antarctic conservation biogeographic regions. *Diversity and Distributions* 22(8):836–840.

Teschke K, Brtnik P, Hain S, Herata H, Liebschner A, Pehlke H & Brey T (2021). Planning marine protected areas under the CCAMLR regime: the case of the Weddell Sea (Antarctica). *Marine Policy* 124:104370.

Teufel L, Pipal A, Schuster KC, Staudinger T & Redl B (2010). Material-dependent growth of human skin bacteria on textiles investigated using challenge tests and DNA genotyping. *Journal of Applied Microbiology* 108(2):450–461.

Thomas ER, van Wessem JM, Roberts J, Isaksson E, Schlosser E, Fudge TJ et al. (2017). Regional Antarctic snow accumulation over the past 1000 years. *Climate of the Past* 13(11):1491–1513.

Thompson DWJ & Solomon S (2002). Interpretation of recent Southern Hemisphere climate change. *Science* 296(5569):895–899.

Thompson DWJ, Solomon S, Kushner PJ, England MH, Grise KM & Karoly DJ (2011). Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience* 4(11):741-749.

Tixier P, Burch P, Massiot-Granier F, Ziegler P, Welsford D, Lea MA et al. (2020). Assessing the impact of toothed whale depredation on socio-ecosystems and fishery management in wide-ranging subantarctic fisheries. *Reviews in Fish Biology and Fisheries* 30:203–217.

Trathan P, Watkins JL, Murray AWA, Brierley AS, Everson I, Goss C et al. (2001). The CCAMLR-2000 krill synoptic survey: a description of the rationale and design. *CCAMLR Science* 8:1–23.

Trathan PN, Garcìa-Borboroglu P, Boersma D, Bost CA, Crawford RJM, Crossin GT et al. (2015). Pollution, habitat loss, fishing, and climate change as critical threats to penguins. *Conservation Biology* 29(1):31–41.

Trathan PN & Grant SM (2020). The South Orkney Islands southern shelf marine protected area: towards the establishment of marine spatial protection within international waters in the Southern Ocean. In: Humphreys J & Clark RWE (eds), *Marine protected areas: science, policy and management*, Elsevier, Amsterdam, 67–98.

Trathan PN, Wienecke B, Barbraud C, Jenouvrier S, Kooyman G, Le Bohec C et al. (2020). The emperor penguin: vulnerable to projected rates of warming and sea ice loss. *Biological Conservation* 241:108216.

Travers T, Lea MA, Alderman R, Terauds A & Shaw J (2021). Bottom-up effect of eradications: the unintended consequences for top-order predators when eradicating invasive prey. *Journal of Applied Ecology* 58(4):801–811.

Trebilco R, Melbourne-Thomas J & Constable AJ (2020). The policy relevance of Southern Ocean food web structure: implications of food web change for fisheries, conservation and carbon sequestration. *Marine Policy* 115:103832.

Tulloch VJD, Plagányi ÉE, Matear R, Brown CJ & Richardson AJ (2018). Ecosystem modelling to quantify the impact of historical whaling on Southern Hemisphere baleen whales. *Fish and Fisheries* 19(1):117–137.

Tully MB, Krummel PB & Klekociuk AR (2019). Trends in Antarctic ozone hole metrics 2001–17. *Journal of Southern Hemisphere Earth Systems Science* 69(1):52–56.

Turnbull JD & Robinson SA (2009). Accumulation of DNA damage in Antarctic mosses: correlations with ultraviolet-B radiation, temperature and turf water content vary among species. *Global Change Biology* 15(2):319–329.

Turnbull JD, Leslie SJ & Robinson SA (2009). Desiccation protects two Antarctic mosses from ultraviolet-B induced DNA damage. *Functional Plant Biology* 36(3):214–221.

Turner J, Lachlan-Cope T, Colwell S & Marshall GJ (2005a). A positive trend in western Antarctic Peninsula precipitation over the last 50 years reflecting regional and Antarctic-wide atmospheric circulation changes. *Annals of Glaciology* 41:85–91.

Turner J, Colwell SR, Marshall GJ, Lachlan-Cope TA, Carleton AM, Jones PD, Lagun V, Reid PA & Iagovkina S (2005b). Antarctic climate change during the last 50 years. *International Journal of Climatology* 25(3):279–294.

Turner J, Barrand NE, Bracegirdle TJ, Convey P, Hodgson DA, Jarvis M et al. (2014). Antarctic climate change and the environment: an update. *Polar Record* 50(3):237–259.

Turner J, Lu H, White I, King JC, Phillips T, Hosking JS, Bracegirdle TJ, Marshall GJ, Mulvaney R & Deb P (2016). Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. *Nature* 535(7612):411–415.

Turner J & Comiso J (2017). Solve Antarctica's sea-ice puzzle. *Nature* 547(7663):275–277.

Turner J, Phillips T, Marshall GJ, Hosking JS, Pope JO, Bracegirdle TJ & Deb P (2017). Unprecedented springtime retreat of Antarctic sea ice in 2016. *Geophysical Research Letters* 44(13):6868–6875.

Turner J, Marshall GJ, Clem K, Colwell S, Phillips T & Lu H (2020a). Antarctic temperature variability and change from station data. *International Journal of Climatology* 40(6):2986–3007.

Turner J, Guarino MV, Arnatt J, Jena B, Marshall GJ, Phillips T, Bajish CC, Clem K, Wang Z, Andersson T, Murphy EJ & Cavanagh R (2020b). Recent decrease of summer sea ice in the Weddell Sea, Antarctica. *Geophysical Research Letters* 47(11):e2020GL087127.

Turney CSM, Fogwill CJ, Klekociuk AR, van Ommen TD, Curran MAJ, Moy AD & Palmer JG (2015). Tropical and mid-latitude forcing of continental Antarctic temperatures. *The Cryosphere* 9(6):2405–2415.

Udy DG, Vance TR, Kiem AS, Holbrook NJ & Curran MAJ (2021). Links between large-scale modes of climate variability and synoptic weather patterns in the southern Indian Ocean. *Journal of Climate* 34(3):883–899. UN (United Nations) (1980). *Convention on the Conservation of Antarctic Marine Living Resources (with annex)*, vol. 1329, United Nations Treaty Series, report no. I-22301, UN, Geneva.

van den Berg H, Manuweera G & Konradsen F (2017). Global trends in the production and use of DDT for control of malaria and other vector-borne diseases. *Malaria Journal* 16:401.

van den Hoff J, McMahon CR, Simpkins GR, Hindell MA, Alderman R & Burton HR (2014). Bottom-up regulation of a pole-ward migratory predator population. *Proceedings of the Royal Society B: Biological Sciences* 281(1782):20132842.

van den Hoff J, Kilpatrick R & Welsford D (2017). Southern elephant seals (*Mirounga leonina* Linn.) depredate toothfish longlines in the midnight zone. *PLOS ONE* 12(2):e0172396.

van den Hoff J, Eriksson C, Burton H & Schulz M (2018). Size-selective feeding by mesopelagic fish can impact ocean surface abundance of small plastic particles. In: Cocca M, Di Pace E, Errico ME, Gentile G, Montarsolo A & Mossotti R (eds), *Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea*, Capri, Italy, 26–29 September 2017, Springer, Cham, Switzerland, 151–157.

van Dorst J, Wilkins D, Crane S, Montgomery K, Zhang E, Spedding T, Hince G & Ferrari B (2021). Microbial community analysis of biopiles in Antarctica provides evidence of successful hydrocarbon biodegradation and initial soil ecosystem recovery. *Environmental Pollution* 290:117977.

van Ommen TD & Morgan V (2010). Snowfall increase in coastal East Antarctica linked with southwest Western Australian drought. *Nature Geoscience* 3(4):267–272.

Van Waerebeek K, Leaper R, Baker AN, Papastavrou V, Thiele D, Findlay K, Donovan G & Ensor P (2010). Odontocetes of the Southern Ocean sanctuary. *Journal of Cetacean Research and Management* 11(3):315–346.

van Wijk EM & Rintoul SR (2014). Freshening drives contraction of Antarctic bottom water in the Australian Antarctic Basin. *Geophysical Research Letters* 41(5):1657–1664.

Vance TR, Roberts JL, Plummer CT, Kiem AS & van Ommen TD (2015). Interdecadal Pacific variability and eastern Australian megadroughts over the last millennium. *Geophysical Research Letters* 42(1):129–137.

Vaughan DG, Comiso JC, Allison I, Carrasco J, Kaser G, Kwok R, Mote P, Murray T, Paul F, Ren J, Rignot E, Solomina O, Steffen K & Zhang T (2013). Observations: cryosphere. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (eds), *Climate change 2013: the physical science basis*, Cambridge University Press, Cambridge, United Kingdom and New York, United States, 317–382.

Velasco-Castrillón A & Stevens MI (2014). Morphological and molecular diversity at a regional scale: a step closer to understanding Antarctic nematode biogeography. *Soil Biology and Biochemistry* 70:272–284.

Velasco-Castrillón A, Gibson JAE & Stevens MI (2014). A review of current Antarctic limno-terrestrial microfauna. *Polar Biology* 37(10):1517–1531.

Velicogna I, Sutterley TC & van den Broeke MR (2014). Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. *Geophysical Research Letters* 41(22):8130–8137.

Veytia D, Corney S, Meiners KM, Kawaguchi S, Murphy EJ & Bestley S (2020). Circumpolar projections of Antarctic krill growth potential. *Nature Climate Change* 10(6):568–575.

Vincent R & Grinbergs A (2002). *Isolation, ingenuity, innovation and experimentation: lessons for Antarctic expeditions from a ramshackle collection of old sheds*, Atlas Cove, Heard Island cultural heritage management plan, Australian Antarctic Division, Kingston, Tasmania.

Vincent R (2004). *Macquarie Island Station, Buckles Bay: Macquarie Island cultural heritage management plan*, draft prepared for the Australian Antarctic Division, Kingston, Tasmania.

Visoiu M (2019). *Flora values assessment and monitoring report: Macquarie Island Nature Reserve and World Heritage Area*, Nature conservation report 19/01, Natural Values Science Section TDoPI, Parks, Water and Environment, Hobart.

Volzke S, McMahon CR, Hindell MA, Burton HR & Wotherspoon SJ (2021). Climate influences on female survival in a declining population of southern elephant seals (*Mirounga leonina*). *Ecology and Evolution* 11(16):11333–11344.

Voskoboinikova O, Detrich III HW, Albertson RC, Postlethwait JH, Ghigliotti L & Pisano E (2017). Evolution reshaped life for the water column: the skeleton of the Antarctic silverfish *Pleuragramma antarctica* Boulenger, 1902. In: Vacchi M, Pisano E & Ghigliotti L (eds), *Advances in polar ecology,* vol. 3, *The Antarctic silverfish: a keystone species in a changing ecosystem*, Springer, Cham, Switzerland, 3–26.

Waller CL, Griffiths HJ, Waluda CM, Thorpe SE, Loaiza I, Moreno B, Pacherres CO & Hughes KA (2017). Microplastics in the Antarctic marine system: an emerging area of research. *Science of the Total Environment* 598:220–227.

Walton DWH (2018). Tourism in the Antarctic. *Antarctic Science* 30(3):147.

Wang G, Hendon HH, Arblaster JM, Lim EP, Abhik S & van Rensch P (2019). Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. *Nature Communications* 10:13.

Wang J, Church JA, Zhang X & Chen X (2021). Reconciling global mean and regional sea level change in projections and observations. *Nature Communications* 12:990.

Wasley J, Robinson SA, Turnbull JD, King DH, Wanek W & Popp M (2012). Bryophyte species composition over moisture gradients in the Windmill Islands, East Antarctica: development of a baseline for monitoring climate change impacts. *Biodiversity* 13(3–4):257–264.

Watters GM, Hinke JT & Reiss CS (2020). Long-term observations from Antarctica demonstrate that mismatched scales of fisheries management and predator-prey interaction lead to erroneous conclusions about precaution. *Scientific Reports* 10:2314.

Webb AL, Hughes KA, Grand MM, Lohan MC & Peck LS (2020). Sources of elevated heavy metal concentrations in sediments and benthic marine invertebrates of the western Antarctic Peninsula. *Science of the Total Environment* 698:134268.

Webster M, Gerland S, Holland M, Hunke E, Kwok R, Lecomte O, Massom R, Perovich D & Sturm M (2018). Snow in the changing sea-ice systems. *Nature Climate Change* 8(11):946–953.

Wege M, Bornemann H, Blix AS, Nordøy ES, Biddle L & Bester MN (2021). Distribution and habitat suitability of Ross seals in a warming ocean. *Frontiers in Marine Science* 8:659430.

Whitehead H (2002). Estimates of the current global population size and historical trajectory for sperm whales. *Marine Ecology Progress Series* 242:295–304.

Wienecke B (2009). Emperor penguin colonies in the Australian Antarctic Territory: how many are there? *Polar Record* 45(4):304–312.

Wienecke B (2010). The history of the discovery of emperor penguin colonies, 1902–2004. *Polar Record* 46(238):271–276.

Wienecke B (2012). Emperor penguins at the West Ice Shelf. *Polar Biology* 35(9):1289–1296.

Wilcox C, Van Sebille E & Hardesty BD (2015). Threat of plastic pollution to seabirds is global, pervasive, and increasing. *Proceedings of the National Academy of Sciences* 112(38):11899–11904.

Williams L, Kristiansen P, Sindel B, Wilson SC & Shaw J (2013). Weeds down under: invasion of the sub-Antarctic wilderness of Macquarie Island. *Plant Protection Quarterly* 28(3):71–72.

Williams LK, Shaw JD, Sindel BM, Wilson SC & Kristiansen P (2018). Longevity, growth and community ecology of invasive *Poa annua* across environmental gradients in the subantarctic. *Basic and Applied Ecology* 29:20–31.

Williams R (1985). The potential impact of a krill fishery upon pelagic fish in the Prydz Bay area of Antarctica. *Polar Biology* 5:1–4.

WMO (World Meteorological Organization) (2018). *Scientific assessment of ozone depletion: 2018*, Global ozone research and monitoring project – report no. 58, WMO, Geneva, Switzerland.

Woehler EJ & Croxall JP (1997). The status and trends of Antarctic and sub-Antarctic seabirds. *Marine Ornithology* 25:43–66.

Wöhrmann APA (1998). Aspects of eco-physiological adaptations in Antarctic fish. In: Di Prisco G, Pisano E & Clarke A (eds), *Fishes of Antarctica: a biological overview*, Springer, Milano, Italy, 119–128.

Worby AP, Geiger CA, Paget MJ, Van Woert ML, Ackley SF & DeLiberty TL (2008). Thickness distribution of Antarctic sea ice. *Journal of Geophysical Research: Oceans* 113(C5):C05S92.

World Population Review (2021). Antarctica population 2021, World Population Review, California, accessed 27 May 2021, https://worldpopulationreview.com/continents/antarctica-population.

Xue L, Cai WJ, Takahashi T, Gao L, Wanninkhof R, Wei M, Li K, Feng L & Yu W (2018). Climatic modulation of surface acidification rates through summertime wind forcing in the Southern Ocean. *Nature Communications* 9:3240.

Yamashita R, Takada H, Nakazawa A, Takahashi A, Ito M, Yamamoto T et al. (2018). Global monitoring of persistent organic pollutants (POPs) using seabird preen gland oil. *Archives of Environmental Contamination and Toxicology* 75(4):545–556.

Yang J, Xiao C, Liu J, Li S & Qin D (in press). Variability of Antarctic sea ice extent over the past 200 years. *Science Bulletin*.

Yates P, Ziegler P, Welsford D, Wotherspoon S, Burch P & Maschette D (2019). Distribution of Antarctic toothfish *Dissostichus mawsoni* along East Antarctica: environmental drivers and management implications. *Fisheries Research* 219:105338.

Young DA, Wright AP, Roberts JL, Warner RC, Young NW, Greenbaum JS, Schroeder DM, Holt JW, Sugden DE, Blankenship DD, Van Ommen TD & Siegert MJ (2011). A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes. *Nature* 474(7349):72–75.

Zhou C, Liang Q, Chen Y, Lei H, Fu Z, Zheng L & Liu R (2019). Mass balance assessment of the Amery Ice Shelf basin, East Antarctica. *Earth and Space Science* 6(10):1987–1999.

Zvěřina O, Láska K, Červenka R, Kuta J, Coufalík P & Komárek J (2014). Analysis of mercury and other heavy metals accumulated in lichen *Usnea antarctica* from James Ross Island, Antarctica. *Environmental Monitoring and Assessment* 186(12):9089–9100.

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