# 1

# INTRODUCTION

## Antarctica and Planet Earth

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### 1.1 Prologue

Antarctica is one of the most enigmatic places on our planet. It pervades the public consciousness as the last great wilderness, inaccessible to most and seemingly almost untouched by human influence. Vast areas of it remain to be explored, including regions below floating ice shelves that are larger than whole countries, and the environment beneath the ice sheet that cannot be observed from the surface or space. It is a land of contrasts, from strikingly beautiful to brutally hostile, from serene and peaceful to violent and unpredictable, and from barren and lifeless to rich in wildlife and biodiversity. Each of these perceptions contains elements of truth, and yet none is fully correct: in many ways, the true nature of Antarctica continues to elude us.

Many visitors to Antarctica comment that it seems other-worldly – to them, Antarctica feels like another planet. Whilst wholly understandable, this belies the key central role that it plays in the functioning of our world. Without Antarctica, and the Southern Ocean that surrounds it, everything on Earth would be different, including our climate, ecosystems, economies, cultures and societies.

The realisation that Antarctica is central to our planet has evolved over time, from the early days of Western exploration, when the imperative was largely to reach the ends of the Earth, to today's understanding of it being at the heart of complex natural and social systems. This understanding is changing rapidly, with new concepts developed and new discoveries made at a seemingly ever-increasing rate. With each, our understanding of the importance of Antarctica to the rest of the world is deepened, as is our knowledge of how vulnerable Antarctica is to human influence, and how swiftly that influence is expanding. Whilst Antarctica does not have a resident local or Indigenous community, it is very much the case that the global population is Antarctica's population.

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It is thus timely to assess our current understanding of Antarctica in the Earth System, reflect on how we gained this understanding, and identify what the grand challenges and key priorities are for future research and activity.

## 1.2 What Makes Antarctica Unique, and Why Is It So Influential?

Antarctica's unique role on our planet stems from its position as Earth's only polar continent, encircled by the expansive Southern Ocean. This geographical configuration acts to partially isolate Antarctica from the rest of the world, as Earth's rotation generates a mid-latitude 'shield' of atmospheric winds and ocean currents flowing predominantly eastward. Few topographic obstacles obstruct them, resulting in the most intense winds (Wallace et al., 2023) and the largest ocean current system (the Antarctic Circumpolar Current; Rintoul & Naveira Garabato, 2013) on Earth (Figure 1.1). Chapter 2 of this book covers the geological and deep-time evolution of Antarctica and the Southern Ocean to reach its present-day state.

Antarctica's relative isolation from the subtropics confers it with an extreme climate. The primarily eastward circulation of the atmosphere-ocean system at Southern Hemisphere mid-latitudes results in substantially weaker poleward transfers of heat and moist air than those occurring over the same latitude range in the Northern Hemisphere (Trenberth, 2022). Consequently, the interior of Antarctica is the coldest and driest region on Earth – a vast, frozen desert, in which the little precipitation that falls can accumulate over thousands to millions of years to form the largest ice sheet on our planet (Rignot et al., 2019). The Antarctic Ice Sheet reaches a thickness of over 4 km at its centre near the South Pole, from where it spreads and thins toward the continental margins, often extending into ice shelves that float over the ocean. The ensuing pole-to-coast gradients in air temperature and surface elevation lead to the emergence of strong winds called katabatics (Parish & Cassano, 2003), which blow persistently toward the coast. On encountering the ocean, these winds may give rise to intense cooling and sea ice production in polynyas (areas of ocean kept persistently clear of ice; Nihashi & Ohshima, 2015). This, in turn, contributes to the growth and advance of sea ice in autumn.

A striking ramification of Antarctica's extreme climate is the global influence it exerts on many important properties of the Earth System. For example, the Antarctic Ice Sheet is the largest freshwater reservoir on Earth and, as such, is a leading determinant of global sea level (IPCC, 2023a). Together with the seasonally-pervasive Antarctic sea ice, the ice sheet can comprise over 65% of the ice area on the planet and is thus a significant contributor to Earth's albedo, i.e., how much solar radiation it reflects back to space (IPCC, 2023a; Meredith et al., 2019). Chapters 6 and 7 of this book provide detail on Antarctic sea ice and the ice sheet, and their importance for climate and sea level rise. Within the Southern Ocean, the Antarctic Circumpolar Current enables a global ocean circulation to exist by connecting the Indian, Pacific and Atlantic basins (Figure 1.1). The vertical exchange of

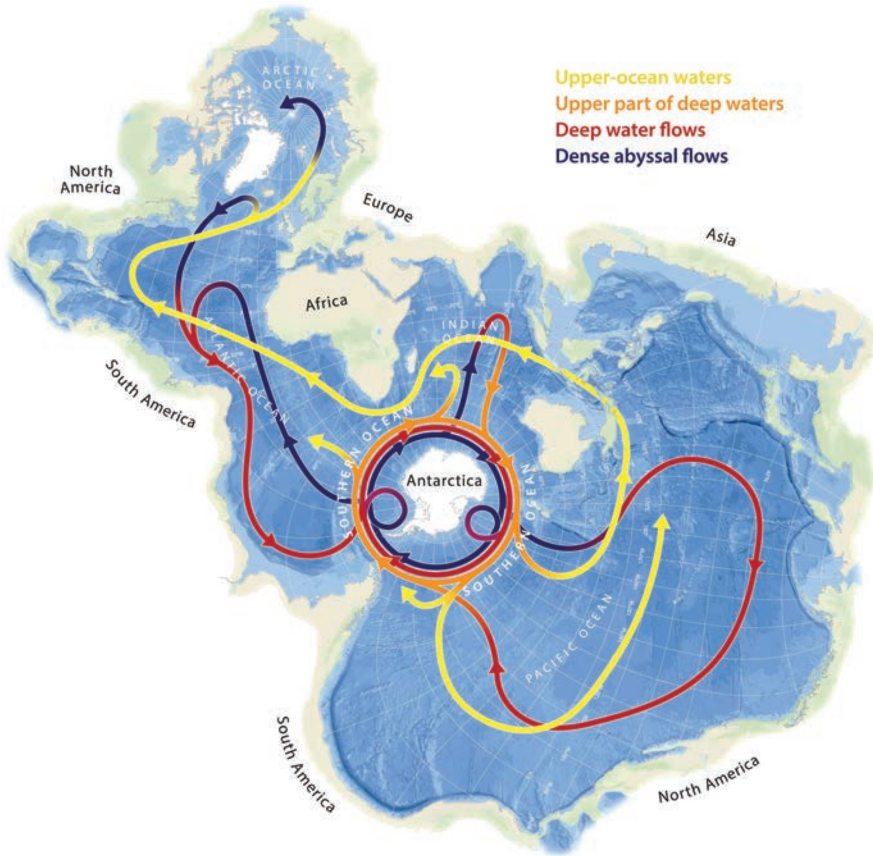


**FIGURE 1.1** The Southern Ocean around Antarctica is central to global ocean circulation. It enables connectivity across the whole planet by linking the Atlantic, Pacific and Indian Ocean basins and is the key site where waters are returned to the surface from depth and then converted into new water masses. The clockwise circulation of waters around Antarctica is the Antarctic Circumpolar Current, the strongest ocean current system in the world.

water masses between the global ocean's surface and deep layers is also focused in the Southern Ocean (Naveira Garabato et al., 2014; Talley, 2013). This is a result of the region's strong wind forcing (which can lift up or push down water; Marshall & Speer, 2012) and prominent seasonal sea ice cycle (which can increase or reduce the density of surface waters, driving the waters to either sink or remain at the surface; Abernathey et al., 2016). Chapter 4 details the drivers and characteristics of Southern Ocean circulation and its global impacts.

Through its vigorous vertical circulation, the Southern Ocean acts as a hotspot for the transfer of climate-critical tracers such as heat and carbon between the atmosphere and vast interior ocean reservoirs (Marshall & Speer, 2012). Accordingly, the region regularly plays a pivotal role in Earth's major climate transitions, such as in contemporary climate change: the Southern Ocean has taken up a large proportion of all anthropogenic heat (~75%) and carbon dioxide (~43%) absorbed by the global ocean since the Industrial Revolution (Meredith et al., 2019). The richness in nutrients of the deep-ocean waters that upwell and flow northward (Figure 1.1) in the Southern Ocean makes the seas around Antarctica some of the most productive on the planet (Arteaga et al., 2020). Since such macronutrients are incompletely consumed by regional primary producers before returning northward, the Southern Ocean also functions as a hub of nutrient supply to the mid- and low-latitude oceans, sustaining a major proportion of global primary production (Sarmiento et al., 2004).

Concomitant with the huge global influence wielded by Antarctica, and despite its relative isolation, the region can be acutely sensitive to environmental perturbations in the rest of the world. For example, atmospheric links enable tropical Pacific climate anomalies such as El Niño to readily alter the persistent low-pressure systems of the Pacific and Atlantic sectors of the Southern Ocean, leading to changes in local ocean circulation (Li & England, 2020), sea ice distribution (Hobbs et al., 2016) and ice shelf melt rates (Paolo et al., 2018). In turn, global-scale variations in atmospheric levels of greenhouse gases and ozone project strongly onto the intensity and geometry of the atmospheric polar vortex, causing changes in the strong Southern Hemisphere eastward winds and associated climate variables (Thompson et al., 2011). Similar far-field connectivity also occurs via the ocean, e.g., water mass modifications in and beyond the subtropics are transferred to the Southern Ocean via ocean circulation (Marshall & Speer, 2012). Chapter 3 describes climate connections between Antarctica and the global atmosphere and tropical oceans.

The intricate, multi-faceted and high-energy interactions between the atmosphere, ocean and cryosphere that proliferate in and around Antarctica make its behaviour highly nonlinear. Accordingly, the regional climate system may exhibit non-intuitive responses to change, abrupt or irreversible transitions, and tipping points (Armstrong McKay et al., 2022; Heinze et al., 2021). Given the reach of changes in Antarctica, such abrupt changes can have profound global consequences.

Antarctic ecosystems are uniquely adapted to cold, highly seasonal polar environments, as detailed in Chapter 9. Fantastic and fascinating examples of cold adaptation in Southern Ocean biota range from 'polar gigantism' (seen in giant sea spiders and other sea-dwelling invertebrates) to antifreeze in the blood of icefish or the staggering biomass of Antarctic krill, which is estimated to be the largest of any multicellular wild animal species on the planet (Atkinson et al., 2009). Biology is an important part of the Southern Ocean's role in the Earth System, contributing to nutrient cycling and biogeochemical uptake of carbon dioxide (see Chapter 5 for details of carbon biogeochemistry around Antarctica). Indeed, Southern Ocean ecosystem services – including regulating services related to carbon dioxide uptake – have been conservatively estimated to contribute ~US$180 billion annually to the welfare of the global population (Stoeckl et al., 2024).

Ecosystems are also connected at a global scale through the seasonal migrations of marine mammals and birds, which occur over the same extent as the global overturning circulation (Figure 1.2; Murphy et al., 2021). Humans have had a profound impact on Antarctic ecosystems through the historical harvesting of whales, seals, finfish, and penguins. Current ecosystem change in the Southern Ocean is driven by a combination of the recovery of these species' populations together with habitat change resulting from climate change (Constable et al., 2014) and other human influences, including fisheries (Chapter 9) and pollution (Chapter 8), with the latter also having impacts on terrestrial ecosystems on the Antarctic continent.

Antarctic and Southern Ocean ecosystems are an important part of the cultural connection that people have with Antarctica – a connection stretching back thousands (if not tens of thousands) of years to Indigenous stories (Roberts et al., 2021). The nature of this connection has also changed over time, from one focused on exploration and exploitation in the 19th century to one that generally values science and environmental protection and that has concern for the future of Antarctica and its ecosystems. The enhanced accessibility of Antarctica, particularly for tourists, as well as the increasing diversity of visitors, has played some role in building levels of care and concern but has also had some direct impacts on Antarctic ecosystems (Huddart & Stott, 2020). Cultural connections between Antarctica and the people of Planet Earth are described in Chapter 11.

Antarctica also has unique arrangements that order how states interact within the region. By the 1940s, seven states (UK, France, Norway, Australia, New Zealand, Chile, and Argentina) had made sovereignty claims covering much of the Antarctic continent, and the United States and Soviet Union also reserved the right to claim territory in Antarctica. The Antarctic Treaty of 1959 was formed to head off the prospect of conflict over sovereignty claims and nuclear testing in the region (Haward & Jackson, 2023). The Treaty preserves the legal position of the seven claimants and other states, but cleverly allows for freedom of scientific investigation and movement for any state within the Treaty (Arpi & McGee, 2022). The Antarctic Treaty is the backbone of the comprehensive Antarctic Treaty System (ATS) which for 60 years has governed the region. The ATS includes the 1980 Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention) relating to conservation of marine living resources such as icefish and krill, and the 1991 Madrid Protocol that provides detailed rules on environmental protection (Press & Constable, 2022). Chapter 10 details Antarctic geopolitics and its unique governance arrangements.

## 1.3 How Has Our Understanding of Antarctica Developed to Its Current State?

Despite its centrality to the functioning of our planet, the historic geographical remoteness of major population centres from Antarctica led to it being the last continent to be explored by humans. Early histories often begin with the crossing of

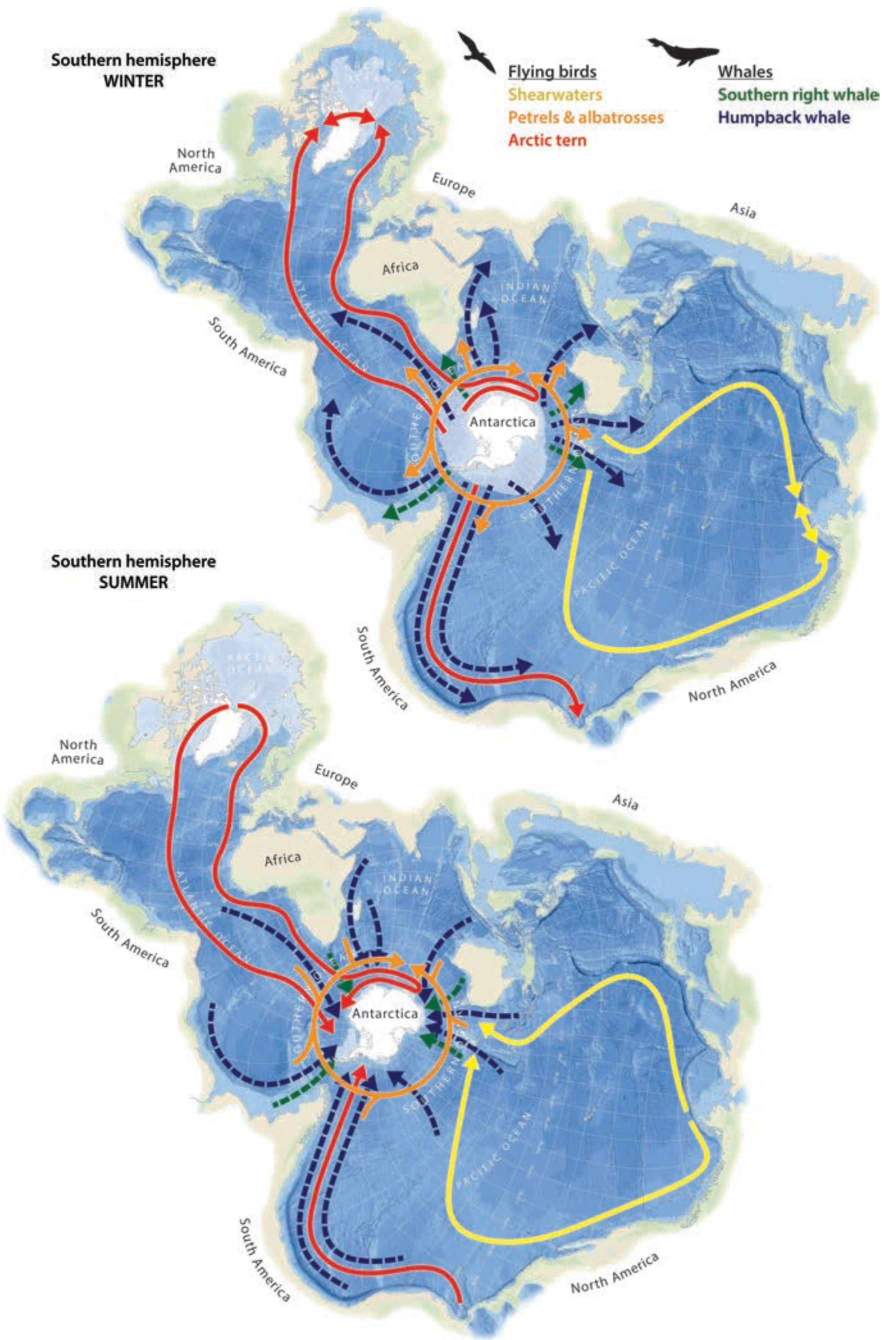


FIGURE 1.2 Global-scale movement patterns of seabird and whale species that undertake large-scale seasonal migrations and play a role in connecting Southern Ocean ecosystems to the rest of the world. Arrows show the direction of movement that sets the winter and summer distributions of these species – away from Antarctica for the winter months (top panel) and towards Antarctica for the summer months (bottom panel). Summer and winter sea ice extent in both polar regions are also shown. Migration information derived from Murphy et al. (2021).

the Antarctic Circle by James Cook in the late 18th century. However, Indigenous art and stories from Australia and Tierra del Fuego point to early knowledge of, and connection to, Southern Ocean ecosystems, such as the migration of whales to and from the south (Hird, 2022; Roberts et al., 2021). The ancient Greeks hypothesised the existence of a great southern continent, needed to balance the known vast land masses to the north, but naturally were not in a position to test this theory. Figure 1.3 shows a timeline of some key events in the developing understanding of Antarctica.

Subsequent to Cook, voyages by early explorers and whalers, such as Fabian Gottlieb von Bellingshausen, Edward Bransfield, and Nathaniel Palmer sighted parts of the Antarctic Peninsula, and expeditions by James Weddell and Dumont d'Urville further explored and charted parts of the continent. During the late 19th and early 20th centuries, the 'Heroic Age' of exploration led to major advances in knowledge of Antarctic geography but also in other disciplines, such as meteorology, geology, biology, and geomagnetism. Explorations, such as Shackleton's Endurance Expedition (1914–1917) and Amundsen's race to the South Pole with Scott, captured the public imagination, persisting up to today. The knowledge gained included understanding of the indifference and sometimes brutality of Antarctic conditions to people and was often won at a great human cost, including loss of life.

Significant scientific advances were made during the era of the Discovery Investigations, which comprised a sequence of expeditions and studies between 1924 and 1951. These had primary foci on developing knowledge of the marine biology and oceanography of the Southern Ocean, with a particular emphasis on attempting to understand the impacts of large-scale whaling and sealing on ecosystems. Although those industries led to the decimation of numerous whale and seal populations, the research conducted produced a remarkable baseline for future studies, and the data continue to be used scientifically today.

The development of coordinated international research in Antarctica took a major step forward with the International Geophysical Year (IGY), which spanned July 1957 to December 1958, and during which many new research stations were established in Antarctica. This international cooperation, and the advance in knowledge it produced, led to the establishment of the 1959 Antarctic Treaty; this is still in force today, serving as a crucial framework to promote international cooperation, scientific research, and environmental protection in Antarctica (Arpi & McGee, 2022).

Since the signing of the Antarctic Treaty, numerous expeditions and research programmes have generated major scientific advances, often with global implications. Relevant aspects are covered in specific chapters here but include the discovery of the ozone hole in the 1980s that led to the 1985 Vienna Convention, and its 1997 Montreal Protocol, which aimed to phase out the use of various ozone-depleting gases; deep ice core science, which has revealed more than a million years of Earth's climatic history; and the discovery of instability of parts of the Antarctic Ice Sheet, with the potential to dramatically impact sea levels globally

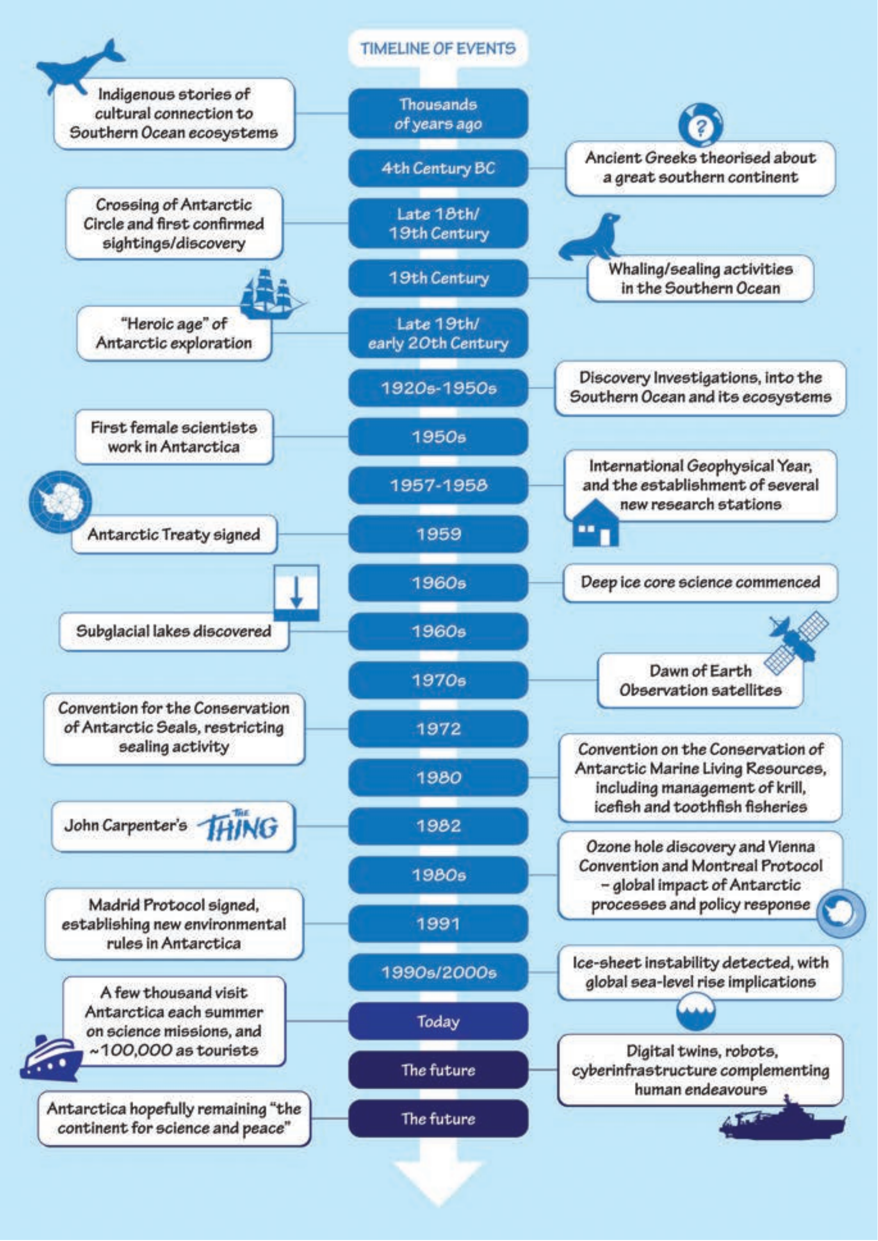


FIGURE 1.3 Timeline schematic of some milestone events in our developing understanding of Antarctica.

over timescales of just a few decades. Scientific progress was spurred enormously by the advent of Earth Observation satellites in the 1970s, which now provide near-continuous measurements of key scientific variables, such as ice sheet elevation and movement, sea ice concentration, ocean temperature, and chlorophyll content.

Our understanding of Antarctica and its global connections is still far from complete, and the accelerating changes that the planet is undergoing emphasise the need to rapidly advance our knowledge. Technological developments, such as autonomous and robotic vehicles, are greatly expanding the scope of what data can be collected, whilst increasingly sophisticated computer simulations of the Antarctic system and the development of machine learning techniques are advancing our ability to reliably predict future changes. Given the vastness of Antarctica and the number of key scientific variables that cannot be measured autonomously, a human presence will be required there for the foreseeable future. Developing mechanisms to combine new, cutting-edge methods with robust, tested ways of collecting data and generating knowledge offers the best scope for optimal scientific progress.

## 1.4 What Are the Most Recent Changes in Antarctica, and Why Are They of Concern?

Antarctica is changing rapidly in many aspects; given its global reach noted above, this is of profound concern. A schematic synopsis of some of the most significant changes and their projected futures is given in Figure 1.4; fuller details of these and other changes are explored in the relevant chapters of this book.

The growth and decay of sea ice around Antarctica represent one of the greatest seasonal changes on the planet. Superposed on this was a small but significant increase in circumpolar extent observed since the start of the satellite era, with record maxima measured in 2013 and 2014. Since 2016, however, sea ice extent has declined dramatically, with record minima observed in 2017, 2022, 2023, and 2024. The full causes of this decline are being established, but it is likely to have profound impacts on climate (via dense water production, albedo, and so on), and also on ecosystems.

The Antarctic Ice Sheet has been losing mass during the satellite era, with losses increasing over the last two decades. This is strongly regional, with West Antarctica, Wilkes Land, and the Antarctic Peninsula most affected, and has been attributed primarily to the strengthening intrusion of warm waters beneath the floating ice shelves. Such intrusion causes thinning and ice shelf collapse, reducing buttressing for land-based glaciers. This can impact on global sea levels; in addition, the strengthened meltwater flux can disrupt the renewal of water masses, and nutrients and particles within the meltwater can perturb the marine ecosystem. Concurrently, new ice-free marine areas become open to colonisation by benthic and pelagic organisms, effectively creating new ecological communities.

Whilst the global average surface temperature has been steadily increasing since the late 1800s, surface temperature trends in Antarctica have experienced strong

| CONFIDENCE: VERY HIGH ● HIGH ◉ MEDIUM ◎ LOW ○ | RECENT CHANGES | FUTURE CHANGE (2100) low emissions | FUTURE CHANGE (2100) high emissions |
|---|---|---|---|
| Antarctic air temperature | ● 0.61°C warming per decade at the South Pole (1989-2018) | ◎ Warming by ~2°C | ◎ Warming by ~5°C or more |
| Antarctic precipitation | ◎ Increase since the 19th century | ○ Could increase by 10-15% | ○ Could increase by as much as a third |
| Accumulated Antarctic contribution to sea level | ● >~7 mm since start of satellite era in ~1992 | ◎ A further ~0.1m (<~3 m by end of 23rd century) | ○ A further ~0.12m but up to ~0.34m depending on which processes dominate. Up to ~16m by end of 23rd century, including loss of WAIS |
| Southern Ocean heat and freshwater content | ● Increase in heat content ~40% of global increase Freshening in surface, mode and intermediate waters, and shelf waters | ◎ Further SST increase by ~<1°C. SO warming by ~0.5°C on average over top 2km | ◎ SST increase by ~3°C. SO warming by ~1°C on average over top 2km |
| Southern Ocean circulation | ◉ Poleward expansion of southern ACC in East Antarctica.<br>◉ Increases in eddy activity.<br>○ Stronger upper ocean overturning.<br>◉ Weaker lower overturning | ◎ Slowdown of lower overturning cell | ◎ Slowdown of lower overturning cell |
| Sea ice area | ● Record summer minima in 2017, 2022 and 2023. Small positive trend from 1979 to 2016 | ○ ~30% loss in February, 15% loss in September (2090-2099) | ○ 90% loss in February, 50% loss in September (2090-2099) |
| Ocean acidification/ reduced calcification | ◎ Aragonite undersaturation already observed in a number of Southern Ocean regions | ○ Surface aragonite undersaturation in ~20% of the Southern Ocean. Species vulnerable to shell dissolution | ○ Surface aragonite undersaturation in >70% of the Southern Ocean. Widespread impacts for calcifying species |
| Climate-driven species range shifts | ◎ Parts of the Antarctic polar ecosystem have contracted southward | ◎ Ongoing range contraction of polar species. Increased southward range shifts of species from northern areas | ○ Significant and/or complete habitat loss for highly cold-adapted and sea ice dependent species |
| Marine ecosystem structure and function | ◉ Spatially variable changes in productivity due to climate-driven changes in nutrient and light environments | ◎ Reduced dominance of Antarctic krill in some regions, increases in salps and changes to benthic and pelagic food webs | ◎ Significant changes to patterns of productivity, food web structure and function, and biologically-driven carbon uptake |
| Terrestrial ecosystems | ◎ Increased growth rates and species turn-over in some regions.<br>◉ Establishment and spread of non-native species | ◎ Increases in the abundance and diversity of many continental taxa. More non-native species | ◎ Significant changes to terrestrial ecosystems and food webs |
| Human presence and cultural connections | ◉ Large-scale increase in human presence and associated impacts | ◉ Continuing cultural connection to Antarctica for global populations. Increased human presence | ◎ Modified cultural connection due to loss of some Antarctic values. Increased human presence |
| Resource use | ◉ Currently managed effectively but with slow progress in achieving large-scale spatial protection | ◎ Resource use and demand for ecosystems services will increase | ◎ Resource use and demand for ecosystems services will increase but with decreased capacity of ecosystems to deliver services |

**FIGURE 1.4** Synopsis of some of the key recent changes in the Antarctica-Southern Ocean system, and projections for their future evolution.

regional variation. For most of the second half of the 20th century, West Antarctica and the Antarctic Peninsula have warmed, at rates comparable to that of the Arctic, though inevitably this warming has not been monotonic. At the South Pole, warming at rates much higher than the global average has been occurring since 1989, with record high annual-average temperatures being observed several times in the 21st century (Clem et al., 2020). The trends in surface air temperature are linked to tropical variability as well as regional atmospheric circulation changes in coastal Antarctica.

Phytoplankton, the base of the Antarctic marine food web, have mainly been increasing in biomass in the Southern Ocean over the last 20 years, though determining whether this is a long-term trend or decadal variation is not yet possible (Pinkerton et al., 2021). Changes in the Southern Ocean environment are affecting plankton blooms, as is the supply of nutrients. Competing effects of mixing and the strengthening of vertical density gradients vary regionally. Many species of Southern Ocean zooplankton are adapted to low temperatures, sea ice and strong seasonality. Ocean warming and acidification can affect krill growth and reproductive success, and the loss of sea ice can result in the loss of an important winter habitat. A poleward contraction of Antarctic krill has been observed in the Atlantic sector of the Southern Ocean, though its full scale remains unclear (IPCC, 2023b). Changes to this species have important ecological and commercial implications, being a prey item for a variety of whales, seals, penguins, etc., as well as the focus of a fishery. The Southern Ocean is particularly susceptible to acidification, with impacts on species that have calcified skeletons and shells. These include many species on the seafloor, and also species higher in the water column that have calcified body parts, such as krill, pteropods ('sea butterflies') and coccolithophores (Figuerola et al., 2021). Globally-important ecosystem services from the Southern Ocean encompass climate regulation, fishery products, tourism, and the cultural value of the region, all underpinned by the preservation of biodiversity (Cavanagh et al., 2021; Stoeckl et al., 2024).

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has an ecosystem approach embedded within its Convention, and it maintains a precautionary approach for the fisheries it manages (Press & Constable, 2022). The recovery of whales, seals and fish from historical overexploitation and seabirds from incidental mortality may be hindered by the effects of climate change. CCAMLR agreed in 2011 to establish a representative system of Marine Protected Areas in the Southern Ocean, but only two such areas have been established so far. Chapter 10 explores the process and politics of protected area establishment in Antarctica and the Southern Ocean.

Terrestrial ecosystems on the Antarctic continent and on sub-Antarctic islands are also vulnerable to human impacts, including climate change. Biodiversity on the Antarctic continent itself is restricted to small ice-free areas and is dominated by mosses, lichens, bacteria, fungi, and invertebrates, such as nematode worms. Quantifying the impacts of changing environmental conditions on terrestrial life in Antarctica is inherently challenging due to remoteness and extreme conditions, as well as the lack of long-term observations, but there is evidence of temperature-related increases in growth rates and of species turnover in some regions (Chown et al., 2022).

Human presence in Antarctica has increased over recent decades. Since the early 1990s tourism in Antarctica has grown continually. Between 1992 and 2020, the number of tourists arriving increased tenfold, rising to 104,897 in the 2022–2023 season. Antarctic tourism has both positive and negative impacts. The Antarctic tourist experience can be both inspirational and educational, fostering public support and investment for the continent's protection. However, it also has a high carbon footprint, and the presence of tourists (and of people generally, including researchers) can potentially disturb wildlife and increase the risks of disease (Wong, 2024) and establishment of non-native species (Leihy et al., 2023). Chapter 9 considers the risks of non-native species for Antarctic and Southern Ocean ecosystems. Globally-generated pollutants, including microplastics and persistent organic pollutants such as DDT, are increasingly detected in the Antarctic and Southern Ocean environment and in the biota of the Southern Ocean, and local effects of pollution are altering environments adjacent to research stations. Chapter 8 details the nature and impacts of pollutants in Antarctica.

Whilst Antarctica and the Southern Ocean mean different things to different people, societal awareness of both the importance and vulnerability of Antarctica has arguably increased in recent years. The portrayal of rapid, climate-driven change in polar regions has shifted from one where the Arctic is regarded as undergoing rapid change whilst Antarctica is relatively stable, to another in which significant recent change in Antarctic and Southern Ocean environments is also recognised. Societal understanding of – and cultural connections to – Antarctica are expressed through the media and through cultural arts. As the accessibility of Antarctica has increased (although, given the very significant cost of travelling to Antarctica, only to a minuscule proportion of the global population), these expressions of connection have also changed (explored in Chapter 11). Antarctica and the Southern Ocean are now more accessible in a physical sense than they have ever been before, and those who visit as tourists or otherwise do so for a broad range of reasons. Overall, the increased accessibility of the region, combined with increased scientific knowledge of global-scale connectivity of the biophysical system, means that perceptions of Antarctica as being isolated and remote are now much less common. The global cultural significance of the Southern Ocean is an important factor in decision-making for Southern Ocean ecosystem management. However, recent research suggests that the global importance of the Southern Ocean ecosystem to people – both in terms of its role in the Earth System, and its cultural values – could be recognised more explicitly when formulating and assessing policies and making decisions (Constable et al., 2023; Roberts et al., 2021).

Over the six decades since its formation, the ATS has been viewed as one of the key success stories of international governance. The region has been kept free from conflict over territorial claims, and the peaceful activities of scientific investigation, environmental protection, and tourism have become the key themes of human use of the continent. Overt geopolitical tension over the continent has, at least until recently, largely been kept behind the closed doors of the ATS meetings, where consensus decision-making processes have sought a common position upon which all states can agree (Haward & Jackson, 2023). However, recently the ATS has experienced two sources of geopolitical tension from events originating outside the ATS. First, the return of great power competition in the international scene has spurred greater contestation over the rules and norms of international institutions (Haward & Jackson, 2023). Over the last decade, there has also been increasing frustration within CCAMLR, and more recently at the Antarctic Treaty Consultative Meeting, over a lack of consensus on marine spatial planning issues, such as three outstanding MPA proposals (Goldsworthy & Brennan, 2021). Second, the Antarctic region is increasingly impacted by biophysical effects of human activities that are sourced from well outside the Antarctic region. The ATS has very limited ability to manage these global environmental problems; the most important role that it can play is in producing timely and high-quality scientific knowledge to inform and push the ambition of international meetings within the Montreal Protocol (ozone depletion), UNFCCC (climate change), and current negotiations on a new marine plastics treaty under the Law of the Sea Convention. To expect any more than this from the ATS is to mischaracterize its regional scope, and to render it vulnerable to unfair criticism that it is failing to solve problems that it was never intended (nor has the capacity) to manage. There have been recent calls for a 'Declaration of Rights of Antarctica' (https://antarcticrights.org/resources/antarctica-declaration/) to recognise legal personality and intrinsic rights for the region, which is arguably based on this type of critique of the ATS. Whilst such calls are well intended, it is important that they do not weaken continuing international support for the ATS.

## 1.5 What Does the Future Hold?

The state of Antarctic climate and ecosystems has already begun to be profoundly influenced by the ongoing global climate and biodiversity crises. These influences are pervasive and extend to virtually all key constituents of the Antarctic-Southern Ocean system. Rapid and ongoing changes noted above raise concerns that this system might have passed tipping points, positioning it on a trajectory toward increasingly rapid and irreversible change.

Although surrounded by varying degrees of uncertainty, projections of the future evolution of the Antarctic-Southern Ocean system regularly highlight a continuation and amplification of the changes in climate and ecosystem variables reported to date. The extent of this amplification, and the potential for reversal of some changes, will be acutely sensitive to how we manage the ongoing climate crisis. Thus, failing to reduce greenhouse gas emissions over coming decades is likely to yield a future in which not only do the changes accelerate but also the risk of crossing multiple tipping points – and reaching scenarios with runaway positive feedback – is magnified. An example of such a risk is that associated with the onset of ice sheet instabilities, which would expectedly lead to increased meltwater influx to the ocean, strengthened on-shelf ocean stratification and an intensified shoreward oceanic heat transport that would reinforce ice sheet instabilities. This scenario is associated with very rapid, multi-metre global sea level rise over the next two centuries, and illustrates how the most catastrophic possible Antarctic futures are contingent on highly nonlinear aspects of the system. Since such nonlinear mechanisms are poorly represented, if not absent, from state-of-the-science Earth System Models, our ability to quantify the risk of highly-damaging changes, and the thresholds for their onset, is very limited.

Substantial future ecosystem changes are likely to occur in Antarctica and across the Southern Ocean over periods of only a few years or decades, as such thresholds are reached and extreme events unfold (Constable et al., 2023). Future climate-driven change at the base of the Southern Ocean food web will have cascading effects on marine ecosystems, with consequences for all trophic levels up to top predators. Future warming and sea ice loss will drive cold-adapted polar species farther south, but such range contractions are ultimately limited for marine species by the presence of the Antarctic continent. This means that some species will eventually run out of habitat space and would therefore be at risk of extinction. The future impacts of warming in the marine environment will be compounded by ongoing ocean acidification. For terrestrial Antarctic ecosystems, future expansion of ice-free areas will provide an expanded habitat area for terrestrial species. Future changes in temperature and liquid water availability will affect the abundance, composition and distribution of Antarctic terrestrial biodiversity. Microscopic algae blooming on the surface of melting snow are also expected to expand in the future as warming creates more of the slushy habitat in which these algae grow (Gray et al., 2020).

Such ecosystem changes will be accompanied by increased human presence in Antarctica and the Southern Ocean, as well as increased demand for globally-important Southern Ocean ecosystem services. Under future climate conditions, Southern Ocean ecosystems will have reduced capacity to meet these needs (Cavanagh et al., 2021). Direct human interventions at a scale sufficient to reduce sensitivities and exposure of cold- and sea ice-adapted species to the impacts of climate change and preserve Southern Ocean ecosystems are unavailable at present (Constable et al., 2023). This means that long-term maintenance of Southern Ocean ecosystems, particularly polar-adapted Antarctic species and coastal systems, can only be achieved by the international community curbing climate change and ocean acidification via reductions in global greenhouse gas emissions in the UNFCCC process. Effective governance and management of local and regional human activities can enhance the resilience of these species and systems, and so reduce the risk of Antarctic ecosystems transitioning into alternative states from which recovery cannot be achieved.

## 1.6 Purpose of This Book

It is clear that, far from being a remote, isolated, and unvarying continent, Antarctica is a place that is central to the functioning of all aspects of Earth, from our climate and ecosystems to our societies and cultures. And it is changing, in some aspects increasingly rapidly, with the potential to generate sudden responses and shifts across the whole planet. Given increasing human pressures on our planet, it is imperative that these linkages and impacts are fully understood, and taken into account by all those making key decisions about our futures.

This book seeks to present a state-of-the-art overview concerning key elements of how Antarctica functions, and how it influences (and is influenced by) humans and the rest of the Earth System. Whilst not all dimensions of Antarctica and the Southern Ocean can be covered here, we have tried to maintain a strong focus on the nature and importance of this connectivity. To achieve this, we have adopted an interdisciplinary and cross-disciplinary perspective, drawing together viewpoints from natural and social sciences. The chapters are discrete, but purposefully interlinked to span the interdisciplinary changes and impacts. For each, we have invited leading practitioners in Antarctic research to summarise the fundamentals and cutting edge of their field and to draw out the grand challenges, immediate key priorities, and routes to progress and solutions that are required. Our hope is that, collectively, this book provides a coherent view across disciplines that will inspire a broadened and deepened perspective on the actions needed now and into the future, to address global change and Antarctica's role therein.

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## References

Abernathey, R. P., et al. (2016). Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geoscience*, *9*(8), 596–601. https://doi.org/10.1038/ngeo2749.

Armstrong McKay, D. I., et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*(6611), eabn7950. https://doi.org/10.1126/science.abn7950.

Arpi, B., & McGee, J. (2022). Rediscovering the importance of Antarctic Law for the early twenty-first century. *Australian Journal of International Affairs*, *76*(3), 248–265. https://doi.org/10.1080/10357718.2022.2056875.

Arteaga, L. A., et al. (2020). Seasonal modulation of phytoplankton biomass in the Southern Ocean. *Nature Communications*, *11*(1), 5364. https://doi.org/10.1038/s41467-020-19157-2.

Atkinson, A., et al. (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. https://doi.org/10.1016/j.dsr.2008.12.007.

Cavanagh, R. D., et al. (2021). Future risk for Southern Ocean ecosystem services under climate change. *Frontiers in Marine Science*, *7*, 21. https://doi.org/10.3389/fmars.2020.615214.

Chown, S. L., et al. (2022). *Antarctic Climate Change and the Environment: A Decadal Synopsis and Recommendations for Action*. Cambridge: Scientific Committee on Antarctic Research.

Clem, K. R., et al. (2020). Record warming at the South Pole during the past three decades. *Nature Climate Change*, *10*(8), 762–770. https://doi.org/10.1038/s41558-020-0815-z.

Constable, A. J., 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. https://doi.org/10.1111/gcb.12623.

Constable, A. J., et al. (2023). *Marine Ecosystem Assessment for the Southern Ocean: Summary for Policymakers*. Zenodo. https://doi.org/10.5281/ZENODO.8359585.

Figuerola, B., et al. (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. https://doi.org/10.3389/fmars.2021.584445.

Goldsworthy, L., & Brennan, E. (2021). Climate change in the Southern Ocean: Is the Commission for the Convention for the Conservation of Antarctic Marine Living Resources doing enough? *Marine Policy*, *130*, 104549. https://doi.org/10.1016/j.marpol.2021.104549.

Gray, A., et al. (2020). Remote sensing reveals Antarctic green snow algae as important terrestrial carbon sink. *Nature Communications*, *11*(1), 2527. https://doi.org/10.1038/s41467-020-16018-w.

Haward, M., & Jackson, A. (2023). Antarctica: Geopolitical challenges and institutional resilience. *The Polar Journal*, *13*(1), 31–48. https://doi.org/10.1080/2154896X.2023.2205237.

Heinze, C., et al. (2021). The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences*, *118*(9), e2008478118. https://doi.org/10.1073/pnas.2008478118.

Hird, C. (2022). Blinding whiteness. *Griffith Review*, *77*, 225–235.

Hobbs, W. R., et al. (2016). A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change*, *143*, 228–250. https://doi.org/10.1016/j.gloplacha.2016.06.008.

Huddart, D., & Stott, T. (2020). Adventure tourism in Antarctica. In D. Huddart, & T. Stott (Eds.), *Adventure Tourism: Environmental Impacts and Management* (pp. 11–50). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-18623-4_2.

IPCC. (2023a). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press. https://doi.org/10.1017/9781009157896.

IPCC. (2023b). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge and New York: Cambridge University Press. https://doi.org/10.1017/9781009325844.

Leihy, R. I., et al. (2023). Introduced and invasive alien species of Antarctica and the Southern Ocean Islands. *Scientific Data*, *10*(1), 200. https://doi.org/10.1038/s41597-023-02113-2.

Li, Q., & England, M. H. (2020). Tropical Indo-Pacific teleconnections to Southern Ocean mixed layer variability. *Geophysical Research Letters*, *47*(15), e2020GL088466. https://doi.org/10.1029/2020GL088466.

Marshall, J., & Speer, K. (2012). Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nature Geoscience*, *5*(3), 171–180. https://doi.org/10.1038/ngeo1391.

Meredith, M., Sommerkorn, M., et al. (2019). Polar regions. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (pp. 203–320). Cambridge and New York: Cambridge University Press. Retrieved from 10.1017/9781009157964.005.

Murphy, E. J., et al. (2021). Global connectivity of Southern Ocean ecosystems. *Frontiers in Ecology and Evolution*, *9*, 624451. https://doi.org/10.3389/fevo.2021.624451.

Naveira Garabato, A. C., et al. (2014). The three-dimensional overturning circulation of the Southern Ocean during the WOCE era. *Progress in Oceanography*, *120*, 41–78. https://doi.org/10.1016/j.pocean.2013.07.018.

Nihashi, S., & Ohshima, K. I. (2015). Circumpolar mapping of Antarctic coastal polynyas and Landfast sea ice: Relationship and variability. *Journal of Climate*, *28*(9), 3650–3670. https://doi.org/10.1175/JCLI-D-14-00369.1.

Paolo, F. S., et al. (2018). Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation. *Nature Geoscience*, *11*(2), 121–126. https://doi.org/10.1038/s41561-017-0033-0.

Parish, T. R., & Cassano, J. J. (2003). The role of Katabatic winds on the Antarctic surface wind regime. *Monthly Weather Review*, *131*(2), 317–333. https://doi.org/10.1175/1520-0493(2003)131<0317:TROKWO>2.0.CO;2.

Pinkerton, M. H., et al. (2021). Evidence for the impact of climate change on primary producers in the Southern Ocean. *Frontiers in Ecology and Evolution*, *9*, 592027. https://doi.org/10.3389/fevo.2021.592027.

Press, A. J., & Constable, A. J. (2022). Conservation law in Antarctica and the Southern Ocean: The Antarctic treaty system, conservation, and environmental protection. *Australian Journal of International Affairs*, *76*(3), 305–323. https://doi.org/10.1080/10357718.2022.2057920.

Rignot, E., et al. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979–2017. *Proceedings of the National Academy of Sciences*, *116*(4), 1095–1103. https://doi.org/10.1073/pnas.1812883116.

Rintoul, S. R., & Naveira Garabato, A. C. (2013). Chapter 18-Dynamics of the Southern Ocean circulation. In G. Siedler, S. M. Griffies, J. Gould, & J. A. Church (Eds.), *International Geophysics* (Vol. 103, pp. 471–492). Academic Press. https://doi.org/10.1016/B978-0-12-391851-2.00018-0.

Roberts, L., et al. (2021). Enabling enduring evidence-based policy for the Southern Ocean through cultural arts practices. *Frontiers in Ecology and Evolution*, *9*, 616089. https://doi.org/10.3389/fevo.2021.616089.

Sarmiento, J. L., et al. (2004). High-latitude controls of thermocline nutrients and low latitude biological productivity. *Nature*, *427*, 56–60. https://doi.org/10.1038/nature02127.

Stoeckl, N., et al. (2024). The value of Antarctic and Southern Ocean ecosystem services. *Nature Reviews Earth & Environment*, *5*(3), 153–155. https://doi.org/10.1038/s43017-024-00523-3.

Talley, L. (2013). Closure of the global overturning circulation through the Indian, Pacific, and Southern Oceans: Schematics and transports. *Oceanography*, *26*(1), 80–97. https://doi.org/10.5670/oceanog.2013.07.

Thompson, D. W. J., et al. (2011). Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience*, *4*(11), 741–749. https://doi.org/10.1038/ngeo1296.

Trenberth, K. E. (2022). Poleward heat transports by the atmosphere and ocean. In *The Changing Flow of Energy through the Climate System* (pp. 121–139). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108979030.012.

Wallace, J. M., et al. (2023). *The Atmospheric General Circulation*. Cambridge: Cambridge University Press.

Wong, C. (2024). Bird-flu threat disrupts Antarctic Penguin studies. *Nature*. https://doi.org/10.1038/d41586-024-00807-0.