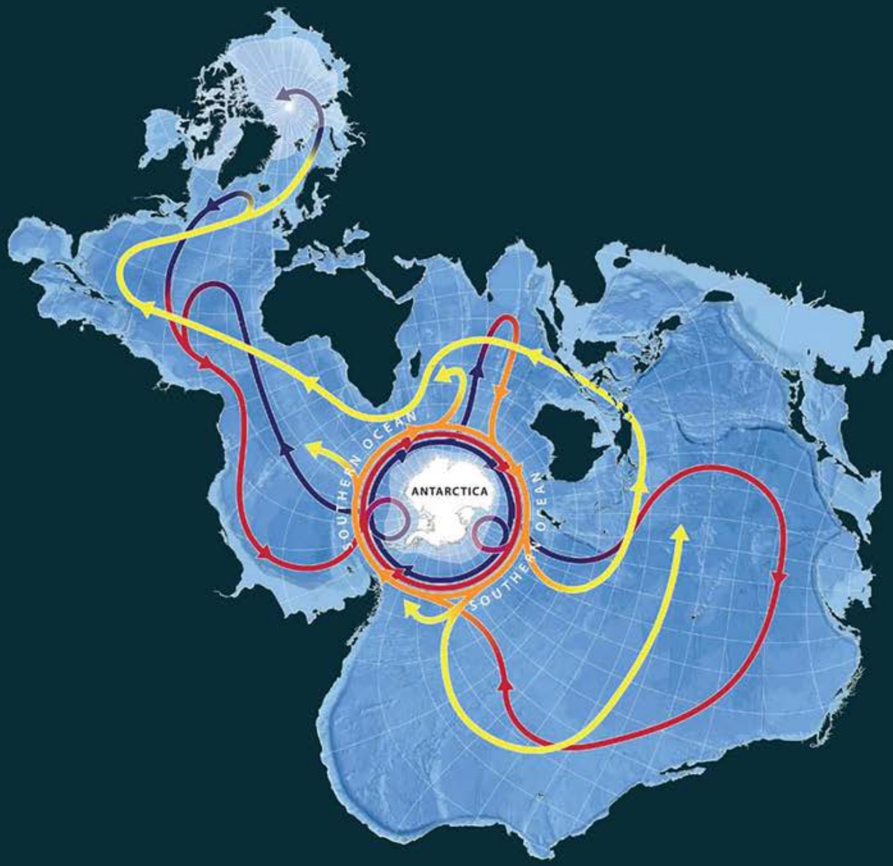
Antarctica and the Earth System



Edited by Michael P. Meredith,
Jess Melbourne-Thomas, Alberto C. Naveira Garabato
and Marilyn Raphael

With Preface by HSH Prince Albert II of Monaco

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‘Antarctica and the Southern Ocean are at the heart of our planet’s functioning, and we must raise awareness about the vulnerability of the polar regions. I extend my heartfelt appreciation to the authors of this work’.

His Serene Highness Prince Albert II of Monaco

‘This remarkable volume reviews everything Antarctic, in a stunning sweep encompassing geophysical history, climate, ice sheets, sea ice, ecology, politics, pollution, and more. A distinguished set of authors and editors has somehow managed to make every chapter not only authoritative but also concise, resulting in a ‘must-have’ book that will enlighten everyone from tourists to senior researchers’.

Susan Solomon, *1999 National Medal of Science Laureate for work on the Antarctic ozone hole*

‘This book effectively synthesizes the latest research and insights, written in a way that makes it an invaluable resource for scholars, policymakers, and anyone interested in the future of Antarctica and our planet. Its interconnecting chapters illuminate the complexities of our relationship with Antarctica, fostering a deeper appreciation for this extraordinary region, and inspiring the next generation of polar researchers’.

Professor Julienne Stroeve, *University College London*

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ANTARCTICA AND THE EARTH SYSTEM

This book presents a state-of-the-art overview of the role that Antarctica and the Southern Ocean play as integral parts of the Earth System.

While often characterised as the last great wilderness on Earth, Antarctica is intimately connected to the rest of the planet, exerting key influences on all places and all people. It is also vulnerable to global changes, especially those driven by humans. This book examines how Antarctica and the Southern Ocean are connected to the rest of the planet, and what these connections mean for the future of Planet Earth and all its inhabitants. It transcends traditional disciplinary boundaries to explore this role across physical, ecological, political, and social systems. Drawing on the latest research findings and thinking, the volume identifies the current leading-order challenges across each of these spheres, highlighting areas where enhanced focus is needed. With the role of Antarctica in the Earth System being one of the most relevant themes of our times, this book will help audiences to understand Antarctica and the Southern Ocean in a global perspective.

Antarctica and the Earth System will be of great interest to a wide range of interdisciplinary students and scholars of Earth sciences, Antarctic studies, polar science, and environmental management.

Michael P. Meredith is an ocean scientist at the British Antarctic Survey and Joint Director of the UK National Climate Science Partnership. He is also Professorial Fellow in Oceanography at Murray Edwards College, University of Cambridge, UK.

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PREFACE TO 'ANTARCTICA AND THE EARTH SYSTEM'

Known as one of the last great wildernesses, Antarctica harbours many secrets that humans have yet to uncover. The fascination evoked by this continent, unanimously dedicated to peace and science, grants it a unique place in our imaginations, cultures, and societies. Although they may sometimes seem distant from our reality and daily concerns, Antarctica and the Southern Ocean are at the heart of our planet's functioning. The changes occurring there have repercussions on a global scale, influencing the climate, ecosystems, and sea level rise.

My expeditions to these isolated realms have left me with a deep sense of humility in the presence of such majestic nature and a profound responsibility toward its vulnerability. For Antarctica is imperilled by the weight of human pressures, whose impacts undermine both marine and terrestrial biodiversity and the essential ecosystem services upon which we rely.

Like a butterfly effect, the changes occurring there disrupt the balance of our societies. These upheavals happen at an increasing speed and with more and more excess: intense heatwaves in both the atmosphere and the ocean, but also a drastic reduction in the thickness of the sea ice reaching new minimum records. We are dangerously approaching tipping points, from which, as we know, we will not be able to return.

The health status of Antarctica is deeply concerning. That is why we must raise awareness about the vulnerability of the polar regions, share our knowledge and experiences, and thus encourage effective conservation actions. This is what my Foundation strives to achieve through the Polar Initiative, with a holistic and unifying approach.

I extend my heartfelt appreciation to the authors of this work, Prof. Michael P. Meredith, Dr. Jess Melbourne-Thomas, Prof. Alberto C. Naveira Garabato, and Prof. Marilyn Raphael, who, in the same spirit of collegiality, have endeavoured to amplify the voices of Antarctic specialists, working together to protect this common heritage of humanity.

His Serene Highness, Prince Albert II of Monaco

THE EDITORS

Dr Jess Melbourne-Thomas works at the interface of science and decision making for climate change adaptation and conservation. She is a principal research scientist with the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) and leads transdisciplinary research to support sustainable marine futures. Jess was a co-convenor of the first Marine Ecosystem Assessment for the Southern Ocean, which was a five-year interdisciplinary collaboration of more than 200 scientists from 19 countries, and was a Lead Author for the IPCC's 2019 Special Report on Ocean and Cryosphere. Jess was the 2020 Tasmanian Australian of the Year and was one of Australia's first 30 Superstars of STEM. She co-founded the Homeward Bound project, which took the largest ever all-female expedition on a leadership journey to Antarctica in 2016 and was one of 12 female scientists globally to have her portrait featured as a constellation on the ceiling of New York's Grand Central Station as part of GE's 2017 Balance the Equation campaign.

Prof. Michael P. Meredith is a marine scientist specialising in polar ocean processes and their role in global circulation and climate change. He is Joint Director of the UK National Climate Science Partnership, senior scientist at the British Antarctic Survey (BAS), and Professorial Fellow in Oceanography at Murray Edwards College, University of Cambridge. Since 1992, Michael has participated in 19 research expeditions to the polar regions, leading 5 of them. He has published more than 200 papers in international journals, is a Fellow of the American Geophysical Union and the Royal Meteorological Society, and served as Coordinating Lead Author for the IPCC's 2019 Special Report on Ocean and Cryosphere. In 2018, Michael was awarded the Tinker-Muse Prize for Science and Policy in Antarctica, in recognition of his contributions to the study of the Southern Ocean and its global impacts, and the Challenger Medal, for exceptional contributions to Marine Science. In 2020, he was awarded the Polar Medal by HM The Queen. In 2021, Michael was elected to serve as President of the Challenger Society for Marine Science, the UK's pre-eminent learned body for research of the ocean.

Prof. Alberto C. Naveira Garabato is an oceanographer interested in the processes governing ocean circulation and its role in climate, with a particular focus on the Southern Ocean and Antarctica. He holds the Regius Chair in Ocean Sciences at the University of Southampton and is an Honorary Fellow of the British Antarctic Survey. His work has been recognised with the Outstanding Early Career Scientist Award (2008) and the Nansen Medal (2023) of the European Geosciences Union, a Philip Leverhulme Prize (2010), a Royal Society Wolfson Research Merit Award (2014), and the Challenger Medal of the Challenger Society for Marine Science (2020). He was the lead proponent of the RoSES programme, which assessed the role of the Southern Ocean in the global carbon cycle; and the founding director of the NEXUSS Centre of Doctoral Training, which is supporting 45 PhD students across ten UK institutions in the use of cutting-edge sensor and autonomous system technologies for environmental science. He is a current awardee of an Advanced Grant of the European Research Council to investigate the role of Southern Ocean sea ice-ocean processes in configuring global ocean circulation.

Prof. Marilyn Raphael is a physical geographer interested in climate variability and change in the high-latitude Southern Hemisphere. Her work focuses on Antarctic sea ice variability, specifically the way in which the sea ice and the large-scale atmospheric circulation interact, thereby creating potential for prediction of Antarctic climate change at the seasonal, interannual and decadal timescales. Marilyn is a Professor of Geography at the University of California, Los Angeles and Director of UCLA's Institute of Environment and Sustainability. A former President of the American Association of Geographers, Marilyn is a Fellow of the American Academy of Arts and Sciences and member of the American Philosophical Society. In 2017, she was named to the Royal Society's Women in Science List of 90 Women and was one of the Scientific Committee on Antarctic Research's Women in Antarctic Science. She is Chair of the Scientific Committee on Antarctic Research's expert group, Antarctic Sea-ice Processes and Climate (ASPeCt). In this role, she promotes research on Antarctic sea ice observations and modelling and coordinates the efforts of the international science community bringing together expertise on the observational and modelling aspects of the climate.

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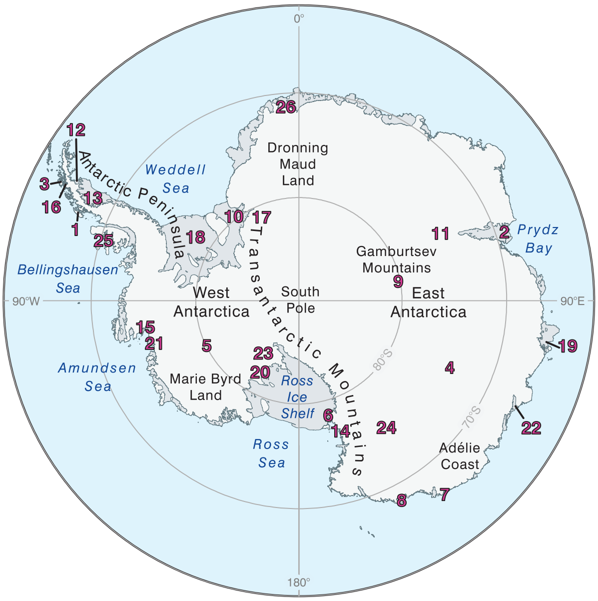
MAPS OF ANTARCTICA AND THE SOUTHERN OCEAN



1. Adelaide Island
2. Amery Ice Shelf
3. Anvers Island
4. Aurora Subglacial Basin
5. Byrd Subglacial Basin
6. Cape Roberts
7. Commonwealth Bay
8. Cook Ice Shelf
9. Dome A
10. Filchner Ice Shelf
11. Lambert Subglacial Basin
12. Larsen B
13. Larsen C Ice Shelf
14. McMurdo Valleys
15. Pine Island Glacier
16. Port Lockroy
17. Recovery Basin
18. Ronne Ice Shelf
19. Shackleton Ice Shelf
20. Siple Coast
21. Thwaites Glacier
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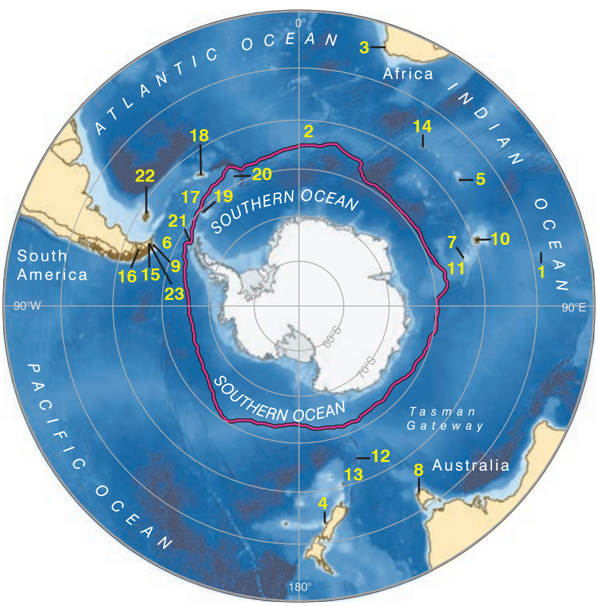
23. Whillans Ice Stream
24. Wilkes Subglacial Basin
25. Wilkins Ice Shelf
26. SANAE IV



1. Amsterdam Island
2. Bouvet Island
3. Cape Town
4. Christchurch
5. Crozet Island
6. Drake Passage
7. Heard Island and McDonald Island
8. Hobart
9. Isla Hermite
10. Kerguelen Island
11. Kerguelen Plateau
12. Macquarie Island
13. Macquarie Ridge
14. Prince Edward Islands (inc Marion Island)
15. Puerto Williams
16. Punta Arenas
17. Scotia Arc
18. South Georgia
19. South Orkney Islands
20. South Sandwich Islands
21. South Shetland Islands
22. Stanley
23. Ushuaia

Average winter sea ice extent (in September 1980-2023)

FIGURE 0.1 (Top) Map of Antarctica and its ice shelves, with selected locations marked. (Bottom). Map of the Southern Ocean, its underlying bathymetry and mean winter sea ice extent, with selected locations marked. Produced by Bonnie Pickard, Mapping and Geographic Information Centre, British Antarctic Survey, UK Research and Innovation, 2024. Data from the SCAR Antarctic Digital Database, 2024. Sea ice extent from 'Fetterer, F., K. Knowles, W. N. Meier, M. Savoie, and A. K. Windnagel. (2017). Sea Ice Index, Version 3 [Data Set]. Boulder, Colorado USA. National Snow and Ice Data Center. https://doi.org/10.7265/N5K072F8. Date Accessed 10-04-2023'. World countries extracted from sources: Esri; National Geographic Society; U.S. Central Intelligence Agency (The World Factbook); Garmin International, Inc. Bathymetry taken from GEBCO Compilation Group (2022) GEBCO_2022 Grid (doi:10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c).

1

INTRODUCTION

Antarctica and Planet Earth

Michael P. Meredith, Jess Melbourne-Thomas, Alberto C. Naveira Garabato, Marilyn Raphael, Jeffrey McGee, and Jamie Oliver

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

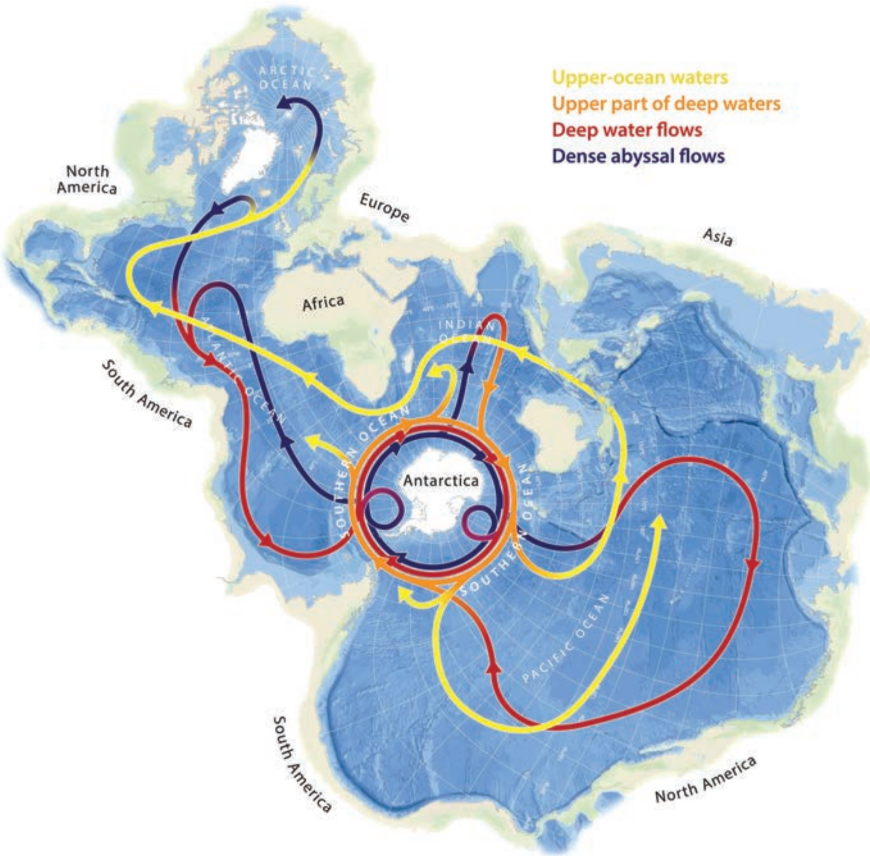

FIGURE 1.1 The Southern Ocean around Antarctica is central to global ocean circulation. It enables connectivity across the whole planet by linking the Atlantic, Pacific and Indian Ocean basins and is the key site where waters are returned to the surface from depth and then converted into new water masses.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

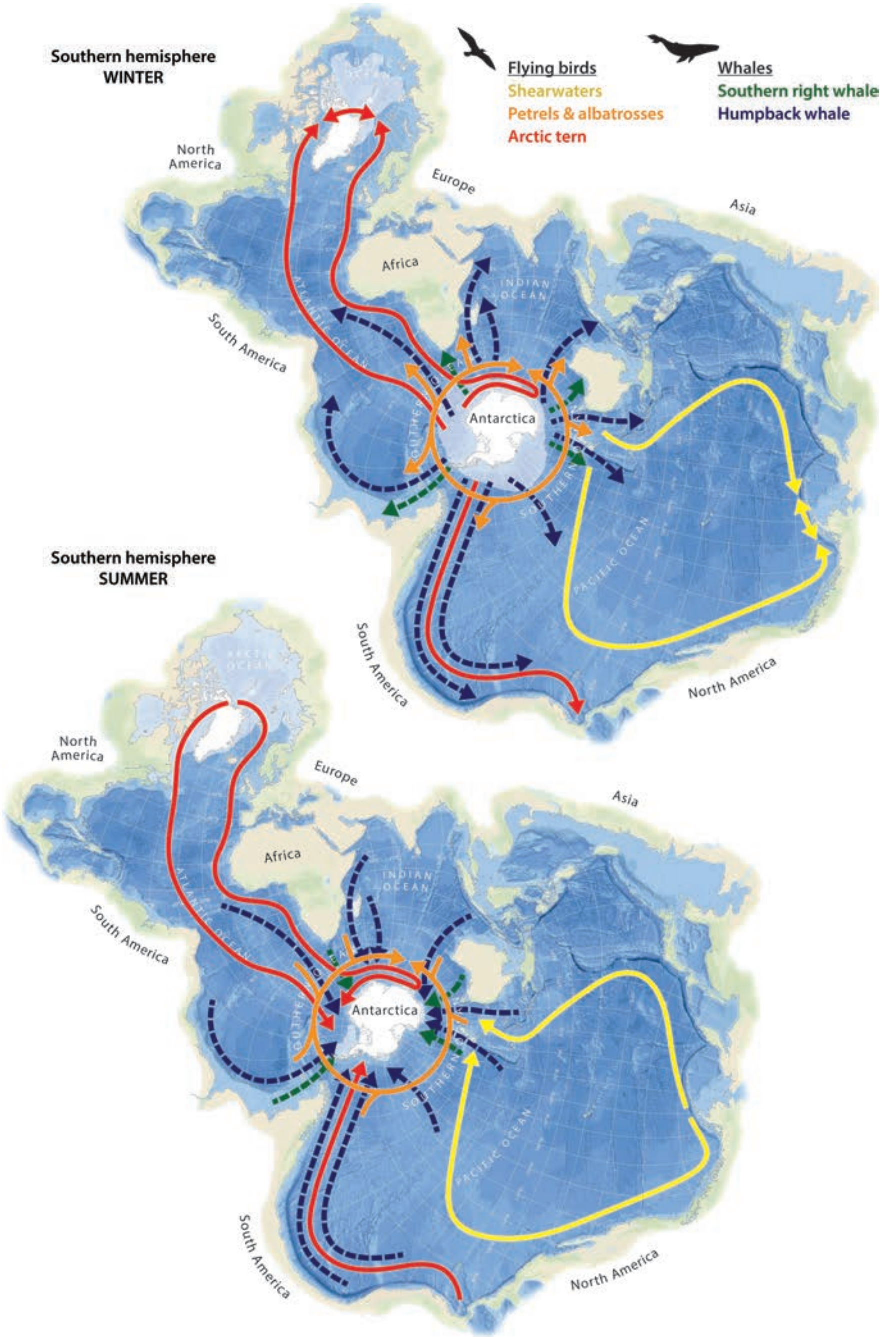

FIGURE 1.2 Global-scale movement patterns of seabird and whale species that undertake large-scale seasonal migrations and play a role in connecting Southern Ocean ecosystems to the rest of the world. Arrows show the direction of movement that sets the winter and summer distributions of these species – 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

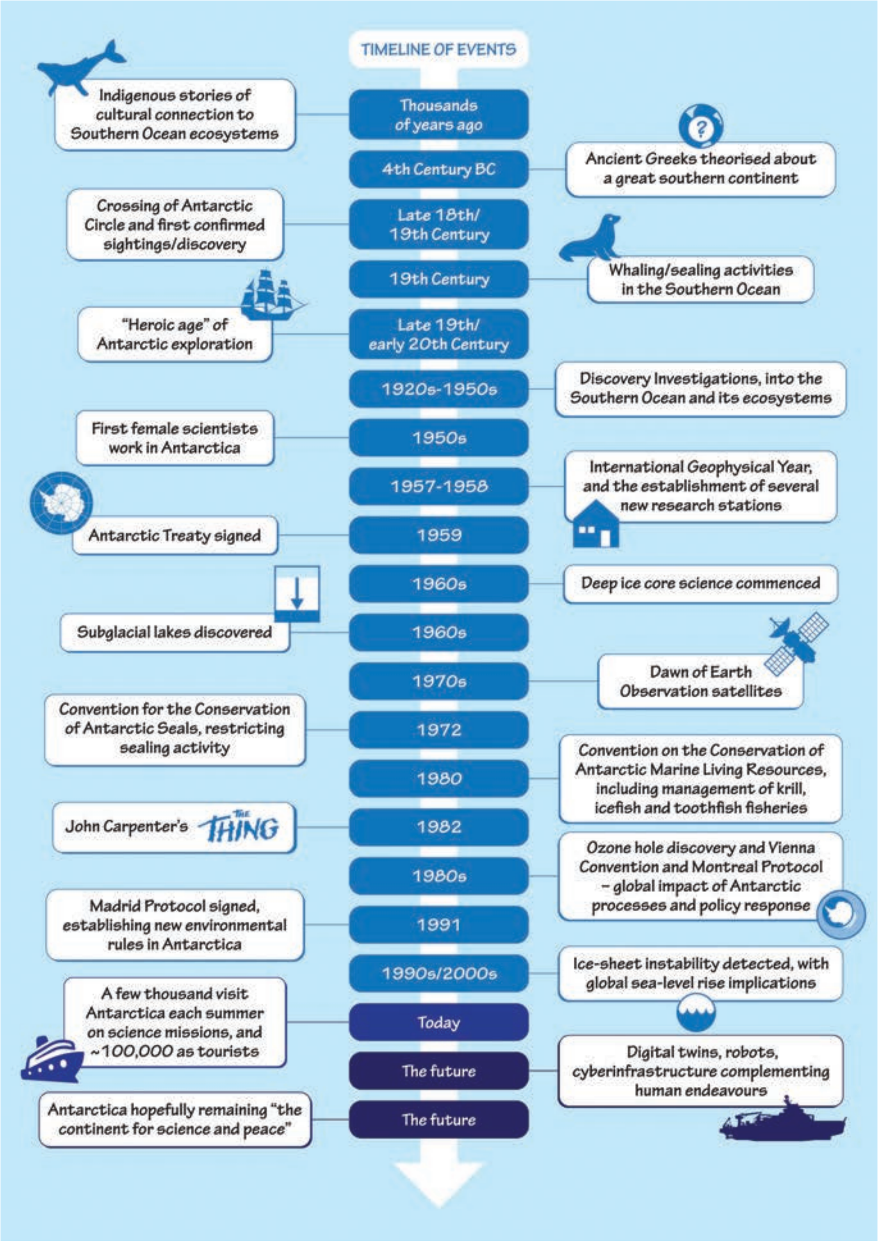

FIGURE 1.3 Timeline schematic of some milestone events in our developing understanding of Antarctica.

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

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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2

GEOLOGICAL AND PALEOCLIMATIC EVOLUTION OF THE SOUTHERN OCEAN–ANTARCTIC SYSTEM

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2.1 Birth of Antarctica and the Southern Ocean

2.1.1 Tectonic Evolution

The Antarctic continent has been located at or very close to the South Pole since around 300 million years ago (Ma; Müller et al., 2019). Prior to ~180 Ma, Antarctica was part of the supercontinent Gondwana, merged together with the other Southern Hemisphere landmasses of South America, Africa, India, Australia and Zealandia. The Pacific portion of West Antarctica was the only sector of Antarctica that was not landlocked, remaining adjacent to an ocean basin. The break-up of Gondwana, and the gradual isolation of Antarctica, led to the evolution of the Southern Ocean (SO) and establishment of the Antarctic Circumpolar Current (ACC). At ~180 Ma, West Gondwana (South America and Africa) separated from East Gondwana (Antarctica, India, Australia and Zealandia), opening the first ocean basin. From ~136 Ma, South America, Africa and India continued to move roughly northwards away from Antarctica. Finally, separation between Australia, Lord Howe Rise, New Zealand and Antarctica occurred from ~90 Ma. The tectonic isolation of Antarctica continued as all these plates separated further, widening all sectors of the SO.

2.1.2 The Antarctica-SO System: From Eocene to Oligocene

Coeval with the progressive tectonic isolation of Antarctica, the global climate transitioned from hot 'greenhouse' conditions during the Late Cretaceous period (~65 Ma) to warm climates of the Paleogene and early Eocene (~65–45 Ma). This tectonic and climate transition was associated with cooler conditions and the first occurrences of small ephemeral Antarctic glaciers during the middle-late

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Eocene (~40 Ma; Carter et al., 2017; Gulick et al., 2017) and large-scale Antarctic glaciation at the Eocene/Oligocene boundary (~34 Ma; Bohaty et al., 2012; Zachos et al., 1994). The Early Eocene Climate Optimum (~53–51 Ma) atmospheric CO_2 concentrations were the highest over the past 66 Ma at ~1600 ppm (CenCO_2PIP Consortium et al., 2023).

The last land bridges connecting Antarctica with Gondwanan continents finally separated during the Eocene, allowing shallow water exchange through both the Drake Passage and Tasman Gateway (Figure 0.1) by around 50 Ma (Bijl et al., 2013; van de Lagemaat et al., 2021). Further deepening of the Tasman Gateway occurred between ~33.5 Ma and 30 Ma, but the Drake Passage remained constricted until <26 Ma (van de Lagemaat et al., 2021). These tectonic events preconditioned the SO for the inception of the ACC but were insufficient to initiate a deep-reaching, modern-style ACC until the Miocene (Sangiorgi et al., 2018; Evangelinos et al., 2024). Nevertheless, these tectonic events left Antarctica entirely isolated and meant that there was a clear circumpolar ocean pathway, which enabled a major reorganisation of SO currents. As the gateways deepened, the subpolar gyres shrank and could no longer transport warm water to the Antarctic coast, resulting in 2–4°C cooling of Antarctic surface waters (Sauermilch et al., 2021). The opening of the Drake Passage and Tasman Gateway, combined with decreasing atmospheric greenhouse gas concentrations, likely both contributed to the glaciation of Antarctica.

2.2 Gradual Cooling of the Antarctica–SO System: From EOT to Late Miocene

2.2.1 From EOT to Late Oligocene (34–23 Ma): Gradual Global Cooling

In Antarctica, ice likely first nucleated on elevated coastal regions and on high topography in the late Eocene (Baatsen et al., 2024). A rapid step-increase in Antarctic ice extent and volume occurred at the Eocene–Oligocene transition (EOT; 34.0–33.5 Ma). Hypotheses for the cause of this expansion include: (1) a large drop in atmospheric CO_2 levels; (2) the development of a modern-like ACC (Kennett, 1977); and (3) internal carbon-cycle feedbacks (Coxall et al., 2005). Numerical oceanic and ice-sheet simulations suggest that the tectonic changes in the main SO gateways alone cannot result in sufficient cooling to explain the ice expansion in Antarctica (e.g., Sauermilch et al., 2021; DeConto and Pollard, 2003). Those simulations show that a substantial drop in CO_2 was necessary to trigger large glaciations and that the opening of the ocean gateways strengthened the regional cooling over Antarctica. The atmospheric CO_2 threshold required to trigger large-scale glaciations over Antarctica remains undetermined. Numerical climate and ice sheet simulations suggest a range of atmospheric CO_2 thresholds from 500 to 900 ppm (Ladant et al., 2014) to glaciate East Antarctica.

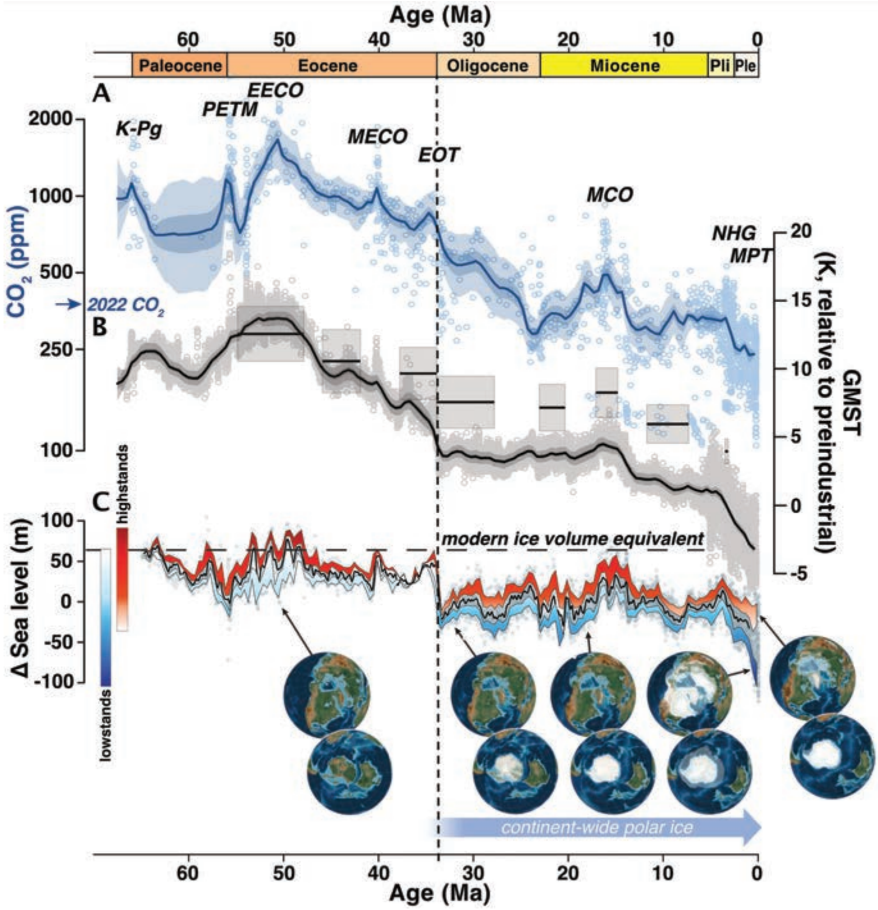

FIGURE 2.1 (A) Atmospheric CO_2 multi-proxy compilation showing a 500-kyr mean statistical reconstruction (median and 50% (dark blue) and 95% (light-blue) (CenCO_2PIP Consortium et al., 2023) and the climate events mentioned in this chapter: EECO, Early Eocene Climatic Optimum; MECO, Middle Eocene Climatic Optimum; EOT, Eocene/Oligocene Transition; MCO, Miocene Climatic Optimum; NHG, onset of Northern Hemisphere Glaciation; and MPT, Mid-Pleistocene Transition. (B) Global mean sea-surface temperature estimated from benthic $\delta^{18}O$ data (Westerhold et al., 2020); individual proxy estimates as symbols, and statistically reconstructed 500-kyr mean values shown as the continuous curve, with 50 and 95% credible intervals. Grey boxes show surface temperature estimates from Ring et al. (2022). (C) Sea level reconstruction (Miller et al., 2020); grey dots are raw data; the solid black line reflects median sea level in a 1-Myr running window. Paleogeographic reconstructions and the growing presence of ice sheets in polar latitudes are shown on the globes (Scotese, 2021). Figure modified from CenCO_2PIP Consortium et al. (2023).

Paleo sea-level records and benthic oxygen isotope records both suggest that Antarctic ice volume fluctuated significantly throughout the Oligocene (34–23 Ma) (Zachos et al., 2008; Rohling et al., 2022). The Cape Roberts sediment records (western Ross Sea) revealed numerous orbitally-paced cycles attributed to oscillations in East Antarctic Ice Sheet (EAIS) extent and volume between 34 Ma and 17 Ma (Naish et al., 2001; Barrett, 2008; Galeotti et al., 2016). Although the magnitude is still debated, estimates of eustatic sea level fluctuations over this period suggest that Antarctic ice volume varied between 15% and 60% of that of the modern ice sheet (Pekar et al., 2006). Coastal temperatures cooled progressively through the Oligocene (Barrett, 2008), although the cooling was subdued compared to elsewhere in the SO (Duncan et al., 2022), and plant species diversity and abundance remained relatively high (Prebble et al., 2006), suggesting that ice coverage remained limited.

The ice sheets of the Oligocene waxed and waned at orbitally-paced timescales and were characterised by a predominantly warm-based glacial regime, in contrast to the modern AIS, which lacks comparable meltwater (Hambrey et al., 1991). This led to selective erosion of the bed (Thomson et al., 2013), as evidenced by the large volumes of glaciogenic sediment deposited on the East Antarctic continental shelf and upper slope at this time (Hochmuth et al., 2020). Sedimentological evidence from marine sediments indicates that the EAIS reached the coast during the early Oligocene (Passchier et al., 2017). The extent of the West Antarctic Ice Sheet (WAIS) during the Oligocene is more uncertain and evidence is contradictory. Sedimentation rate records from the Weddell Sea and Ross Sea suggest increased erosion in West Antarctica following the EOT, implying the expansion of an ice sheet over West Antarctica, fostered by a paleotopography with a land area ~20% larger than today (Wilson et al., 2013; Paxman et al., 2019). By comparison, present-day West Antarctic bed topography is mostly below sea level (Morlighem et al., 2020; Figure 2.2). Other geological evidence contradicts this analysis and suggests the existence of shallow bathymetric troughs and inland seaways in West Antarctica that may have facilitated warm water intrusions, thus inhibiting the expansion of an ice sheet over West Antarctica during the early Oligocene (Coenen et al., 2020; Uenzelmann-Neben et al., 2022).

While the AIS extent remained limited, water-mass signatures retrieved from SO sediment records spanning the last 31 Myr clearly suggest that the ACC remained shallow during the Oligocene until the mid-Miocene (Evangelinos et al., 2024). These data also suggest that a water mass resembling Circumpolar Deep Water (CDW), as part of the deep layer of the ACC, already formed at that time, fostered by efficient deep water exchange between the Atlantic and Indian Ocean, but not between the Indian and Pacific Ocean.

2.2.2 Gradual Cooling toward Polar Conditions: The Miocene Period (23–5.3 Ma)

The early to mid-Miocene (23–14 Ma) provides insight into the behaviour of the AIS during a period when Antarctic paleotopography continued to evolve towards the

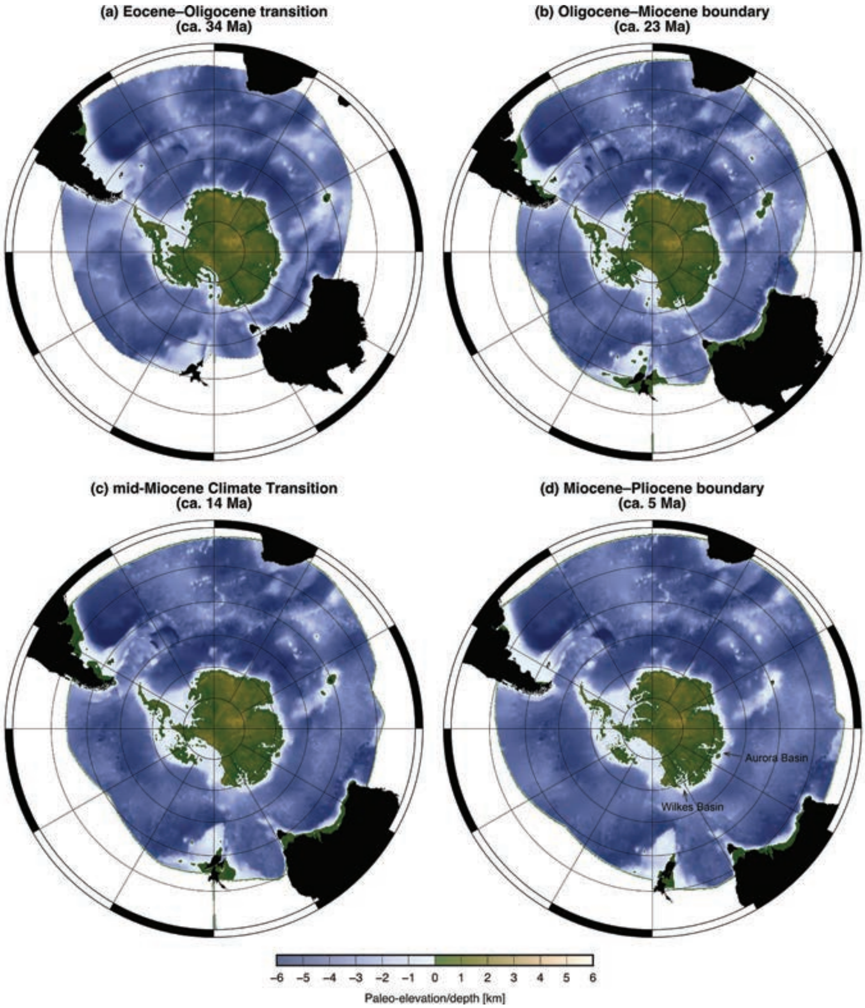

FIGURE 2.2 Reconstructed evolution of the paleogeography, paleotopography and paleobathymetry of Antarctica and the Southern Ocean from (a) the Eocene–Oligocene transition (~34 Ma) through (b) the Oligocene–Miocene boundary (~23 Ma) and (c) the mid-Miocene Climate Transition (~14 Ma) to (d) the Miocene–Pliocene boundary (~5 Ma) (Paxman et al., 2019; Hochmuth et al., 2020).

modern configuration and atmospheric CO_2 fluctuated between 200 and 400 ppm, with potential peaks at ~800 ppm during interglacial periods of the mid-Miocene Climatic Optimum (MCO; 17.0–14.8 Ma) (CenCO_2PIP Consortium et al., 2023). During MCO warm intervals, mean summer temperatures in the McMurdo Dry Valleys were 5–7°C, up to 20°C warmer than the present-day (Lewis et al., 2008;

Lewis and Ashworth, 2016). Sea-surface temperatures during the MCO peaked at around 11–17°C off the Adelie Coast (Sangiorgi et al., 2018) and 6–10°C in the Ross Sea (Levy et al., 2016). Warm interglacials of the MCO were characterised by the presence of temperate tundra vegetation (*Nothofagus*, shrubs, grasses and mosses) in coastal lowlands and warm oligotrophic waters in the SO (Warny et al., 2009; Sangiorgi et al., 2018). Neodymium isotope signatures suggest that the strengthening of Atlantic Meridional Overturning Circulation (AMOC) (Via and Thomas, 2006) fostered the inflow of Atlantic deep water masses into the CDW during the early Miocene (Evangelinos et al., 2024).

Far-field eustatic sea-level reconstructions and benthic oxygen isotope records suggest sea-level oscillations of 40–60 m (Lear et al., 2008; Miller et al., 2020), implying periods of near-complete loss of Antarctic land ice. Marine-based portions of the ice sheet repeatedly retreated inland, leaving open-water conditions in most of the marine-based sectors of Antarctica during warm intervals of the MCO (Naish et al., 2001, Sugden and Denton, 2004; Pierce et al., 2017). Geochemical and petrographic analysis of Ross Sea sediment records indicates that a larger-than-present WAIS expanded to cover most of the shallow continental shelf at around 17.8–17.4 Ma (up to 15 metres sea level equivalent compared to 4.5 m today; Marschalek et al., 2021). Terrestrial portions of the EAIS persisted during retreat phases, with the ice margins receded from the coastline and surrounded by tundra (Levy et al., 2016; Sangiorgi et al., 2018; Chorley et al., 2022). The AIS volume during the MCO is simulated to have been 85–90% of the modern-day EAIS (Halberstadt et al., 2021), with an associated sea-level contribution estimated at 30–36 m (Gasson et al., 2016). Total melting of the WAIS during peak warm intervals of the MCO combined with partial loss of the EAIS can explain the inferred magnitude of MCO sea-level oscillations.

The mid- to late-Miocene was characterised by the gradual establishment of an arid polar climate and a persistent continental-scale AIS. During the mid-Miocene Climate Transition (MCT; ~14.8–13.8 Ma), terrestrial evidence from the Transantarctic Mountains indicates cooling of 8°C (Lewis et al., 2008; Lewis and Ashworth, 2016). Although plant and animal fossil records indicate that coastal areas of Antarctica were still ice-free during MCT interglacials (Lewis and Ashworth, 2015; Sangiorgi et al., 2018), glacial intervals progressively intensified, causing the AIS to expand across the marine-based sectors (Shevenell et al., 2008; Holbourn et al., 2018). This cooling was accompanied by the establishment of widespread pan-Antarctic perennial sea-ice cover for the first time since the early Oligocene (Levy et al., 2016; Bijl et al., 2018; Sangiorgi et al., 2018; Halberstadt et al., 2021). By the end of the MCT, a modern-like CDW was established, as a result of the potential inflow of Pacific deep waters, as well as the strengthening of Atlantic and Indian inflows, into CDW via the Drake Passage (Evangelinos et al., 2024). Geological and geochemical evidence suggests major tectonic changes in the Drake Passage, such as the development and deepening of an oceanic gateway along the southern Scotia Ridge until after 12 Ma that would have fostered such an inflow of Pacific deep waters (Dalziel et al., 2013). Based on the neodymium isotope records, the emergence of a well-mixed CDW – as part of the ACC – connecting all three ocean basins was established at the end of the MCT ~12 Ma, but granulometry of the SO sediment records indicates that the ACC speed remained low until at least the late Miocene (~10 Ma; Evangelinos et al., 2024).

After the MCT and throughout the late Miocene, the terrestrial sectors of the ice sheet became increasingly cold-based and less-erosive (Sugden et al., 1999). The AIS is inferred to have stabilised during the late Miocene, with cosmogenic nuclide evidence suggesting that the EAIS draining into the Ross Sea has not retreated significantly onto land since ~8 Ma (Shakun et al., 2018). SO sediment records indicate that ACC depth and speed resembled the present-day by ~10 Ma suggesting that the establishment of polar conditions in the Antarctic since the MCT led to the steepening of equator-to-pole air and sea temperature and density gradients and, hence, to the strengthening of the westerly winds driving the ACC (Evangelinos et al., 2024).

2.3 The Emergence of a Bi-Polar World: The Plio-Pleistocene Period

2.3.1 The Pliocene (5.3–2.6 Ma): A Future Analogue of the SO–Antarctic System?

During the Pliocene, and especially the mid-Pliocene Warm Period (3.3–3.0 Ma), reconstructions suggest that atmospheric CO_2 concentrations were substantially higher ~370 ppm than pre-industrial value of 280ppm (de la Vega et al., 2020), leading to average global temperatures that were 2–3°C warmer. This is comparable to low-end emission scenarios for the end of the 21st century (shared socioeconomic pathways SSP2–2.6 to SSP2–4.5; Meinshausen et al., 2020). Furthermore, the tectonic boundary conditions were similar to present (Haywood et al., 2013), but with smaller Antarctic and Greenland Ice Sheets (Dutton et al., 2015), so this interval provides a useful geological analogue for ongoing anthropogenic climate warming.

The mid-Pliocene was characterised by globally weak meridional temperature gradients and reduced sea-ice concentrations relative to modern in both hemispheres (Whitehead et al., 2005; Knies et al., 2014). Warmer SO sea-surface temperatures, reduced sea ice (Escutia et al., 2009) and more southerly westerly winds relative to pre-industrial conditions (Li et al., 2015; Abell et al., 2021) would have facilitated access of warm CDW onto the continental shelves, likely also contributing to a more retreated AIS (Naish et al., 2009; Cook et al., 2013). Marine sedimentary and geochemical records indicate that there may have been episodic retreat and/or collapse of the marine-based portions in both West Antarctica (e.g., Ross Sea, Naish et al., 2009) and East Antarctica (Adelie/George V Land, Cook et al., 2013; Patterson et al., 2014. Wilkes Land, Williams et al., 2010). Data-model comparisons based on benthic carbon isotopes and simulated ocean ventilation ages are consistent with enhanced Antarctic Bottom Water (AABW) formation and increased ventilation of the SO, in agreement with mid-Pliocene proxy reconstructions showing weak SO stratification (Zhang et al., 2013).

Reconstructed sea-level estimates for the warm intervals of the mid-Pliocene (3.3–3.0 Ma) range from 5 to 25 m above present (Dumitru et al., 2019; Grant et al., 2019). Numerical simulations show a similarly wide range of Antarctic sea-level contributions, such as 6–21 m (Golledge et al., 2017a, DeConto et al., 2021). It is difficult to disentangle the magnitude of the AIS contribution to global mean sea-level rise at that time, due to proxy uncertainties and challenges related to glacio-isostatic adjustment and dynamic topography. The current WAIS hosts an ice volume of about 5.3 m sea level equivalent and the EAIS holds a volume of 52.2 m sea level equivalent (Morlighem et al., 2020), with a further 7.42 m sea level equivalent in Greenland (Morlighem et al., 2017). Even if the entire Greenland Ice Sheet was absent in the mid-Pliocene, significant ice loss from the marine-based margins of East Antarctica as well as loss of the entire WAIS would be required to explain the upper sea-level estimates (Miller et al., 2012; Grant et al., 2019).

2.3.2 Establishment of the Bi-Polar World (2.7 Ma–Present): A Two-Step Process

During the Pliocene-Pleistocene Transition, global climate abruptly cooled, which enabled the progressive expansion of the Northern Hemisphere ice sheets at ~2.7 Ma (Ravelo et al., 2004) and the establishment of the Pleistocene bi-polar world (Zachos et al., 2001). Numerous factors have been hypothesised to have contributed to the onset of cooling and Northern Hemisphere glaciation, including insolation changes (Maslin et al., 1998) and a decline in atmospheric CO_2 concentrations to a threshold of ~300 ppm between 2.8 and 2.5 Ma (DeConto et al., 2008; Lunt et al., 2008; Hönisch et al., 2009). Ice volume and sea-level fluctuations, which were previously dominated by advance and retreat of the AIS, became largely influenced by the periodic growth and decay of the Laurentide and Eurasian ice sheets (Rohling et al., 2022).

Gradual increases in the severity of glacial conditions (colder with larger ice sheets) occurred across the Mid-Pleistocene Transition (MPT) from 1.2 Ma to 800,000 years ago, when the periodicity of cold glacial to warm interglacial climate states switched from 41,000 years to 100,000 years (Ruddiman et al., 1989). Major changes in ocean circulation and carbon cycling in the SO likely contributed to cooling across the MPT via increased seasonal sea-ice extent (McKay et al., 2012a), increased water-column stratification south of the Polar Front (Sigman et al., 2004, Hasenfratz et al., 2019) and increased biological productivity north of the Polar Front associated with enhanced iron fertilisation (Cortese et al., 2004; Martínez-Garcia et al., 2011). For a review of the mechanisms associated with the aforementioned climate feedbacks, see Berends et al. (2021). New continuous million-year-old ice core records are anticipated in the coming years and will improve our understanding of the processes that occurred across the MPT.

2.3.3 Antarctic Ice Sheet Dynamics in the Late Pleistocene

The Pleistocene epoch has the best documented global and regional climate records, including high-resolution Antarctic ice core records going back 800 kyr, so climate forcing and changes in the ice sheet can be resolved on orbital (tens of thousands of years) to centennial timescales. Furthermore, global boundary conditions were similar to the modern-day, including AIS subglacial topography, continental configurations and global ocean circulation patterns, such that an understanding of the climate system behaviour during this period is useful for informing future climate states.

The marine-based portions of the AIS are susceptible to retreat due to atmosphere and ocean warming through a combination of ice-shelf thinning or collapse, and marine ice sheet instability (Jamieson et al., 2012). Pleistocene interglacials provide a good target to understanding climate thresholds because certain 'super-interglacials', such as Marine Isotope Stage (MIS) 5e (129–116 ka) and MIS 11 (424–395 ka), were warmer than the pre-industrial Holocene by ~0.5–2°C globally, and by up to 2–4°C for a few thousand years in Antarctica (Jouzel et al., 2007; Yin and Berger, 2015). Global mean sea-level reconstructions require ice loss from the AIS during peak warm conditions for MIS 5e (<5m, Dumitru et al., 2023; 6–9m, Dutton et al., 2015), beyond partial ice loss from Greenland alone. Asynchronous meltwater contributions from Greenland and the AIS have been proposed, including a dominant Antarctic sea-level contribution to the early MIS 5e sea-level peak at ~129 ka in response to ocean warming (Rohling et al., 2019; Barnett et al., 2023). These past changes are not direct analogues for present-day or near-future anthropogenic climate change but are invaluable for assessing millennial-scale ice-sheet behaviour and the processes and feedbacks involved. Notably, such behaviour cannot be determined from the relatively short record of satellite observations, since the ice sheet and ocean remain out of equilibrium with the climate due to their long response timescales.

Given the sensitivity of West Antarctic catchments, such as the Pine Island/Thwaites Glacier system (Amundsen Sea Embayment) and the Siple Coast (Ross Sea) to ocean warming in numerical models (Golledge et al., 2017b; Clark et al., 2020), a partial or full collapse of the WAIS has been suspected for recent warm interglacials such as MIS 5e and/or MIS 11. Collapse of the WAIS during MIS 11 has also been simulated in models, which suggest an overall Antarctic sea-level contribution during this interval of ~4–8 m (Mas e Braga et al., 2021). However, geological evidence supporting or refuting WAIS collapse remains equivocal. The presence of a trans-Antarctic seaway between the Weddell and Ross seas during at least one late Pleistocene interglacial has been suggested (Scherer et al., 1998; Barnes and Hillenbrand, 2010; Lau et al., 2023), while sediment cores from the Ross Sea shelf imply loss of the Ross Ice Shelf during MIS 5e or MIS 7, providing indirect evidence for WAIS deglaciation (McKay et al., 2012b). West Antarctic blue-ice records also provide evidence for regional climate changes expected from WAIS collapse (Steig et al., 2015), and for ice sheet changes in the Weddell Sea Embayment (Turney et al., 2020; Figure 2.3b).

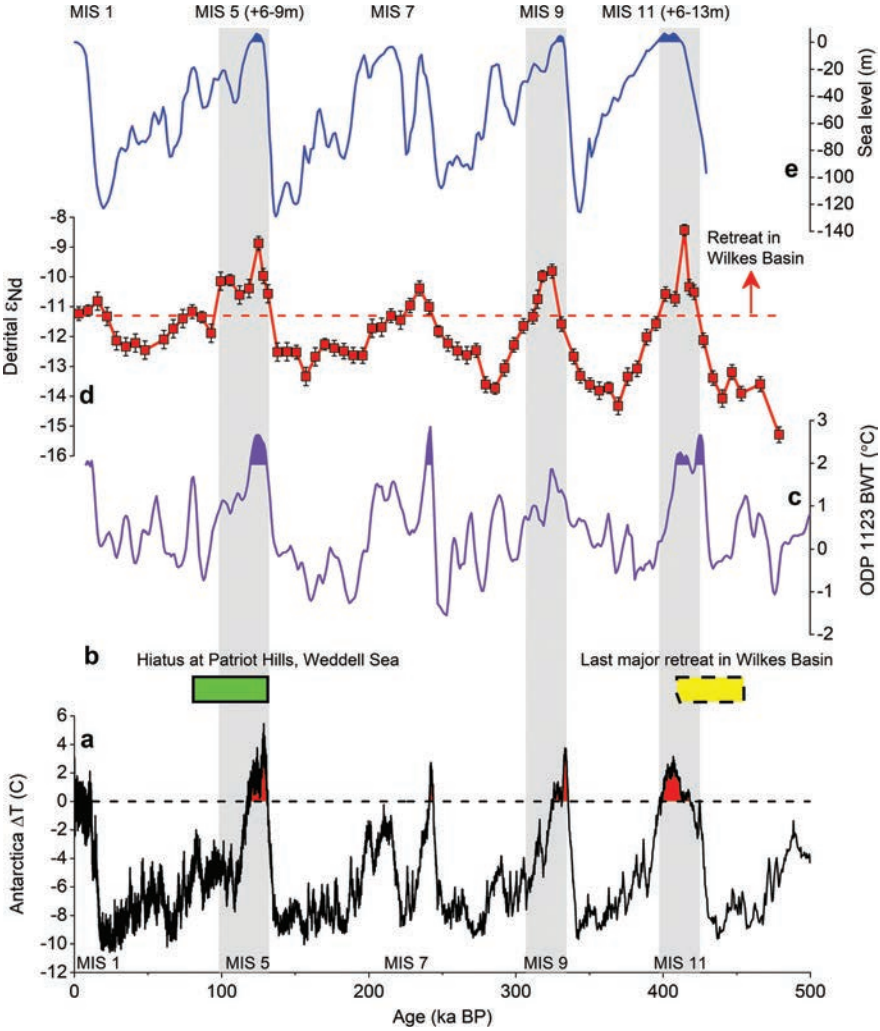

FIGURE 2.3 Late Pleistocene Antarctic Ice Sheet evolution. (a) Antarctic temperature change (ΔT) from δD in EDC ice core (Jouzel et al., 2007). (b) Timings of a hiatus at Patriot Hills, indicating grounding line retreat in the Weddell Sea sector of the WAIS (Turney et al., 2020), and the last major retreat in the Wilkes Subglacial Basin of the EAIS (95% confidence interval; Blackburn et al., 2020). (c) Southern Ocean bottom-water temperature (BWT) from benthic foraminiferal Mg/Ca at ODP Site 1123 (Elderfield et al., 2012). (d) Detrital sediment Nd isotopes at IODP Site U1361 (Wilson et al., 2018), indicating ice sheet retreat (grey bars) in the Wilkes Subglacial Basin. (e) Global sea-level proxy from benthic $\delta^{18}O$ (Waelbroeck et al., 2002), with marine isotope stages (MIS) and selected sea-level estimates (Dutton et al., 2015). Shading in (a, c, e) and red dashed line in (d) enable comparison to late Holocene values.

Much of the EAIS is terrestrial-based and these portions appear to have remained intact since the late Miocene (Shakun et al., 2018). However, nearly one-third of the ice in East Antarctica is located in marine-based catchments within the Wilkes, Aurora and Recovery Subglacial Basins (Figure 0.1), which may have experienced variability during the Pleistocene. There are only limited sedimentary records from these remote regions, of which the Wilkes Subglacial Basin is the best investigated due to the Integrated Ocean Drilling Program Expedition 318 (Escutia et al., 2011). Sediment provenance records from offshore of the Wilkes Subglacial Basin indicate ice-margin retreat during MIS 5e, MIS 9 and MIS 11 (Wilson et al., 2018; Iizuka et al., 2023) (Figure 2.3). Furthermore, differing responses to these warm interglacials compared to the Holocene and MIS 7 indicate that retreat may have occurred when Antarctic air temperatures were at least 2°C warmer than pre-industrial for ~2,500 years or more (Figure 2.3). Despite suggesting a contribution to late Pleistocene interglacial sea levels from the EAIS, those data are not able to quantify the extent of retreat or the sea-level contribution. Independent evidence from the geochemistry of subglacial opal and calcite precipitates in the Wilkes Subglacial Basin suggests a major ice-margin retreat during MIS 11 (Figure 2.3b), with a potential sea-level contribution of up to 3–4 metres, but only minor changes during subsequent interglacials (Blackburn et al., 2020). In addition, ice-core evidence for ice-sheet elevation at Talos Dome during recent interglacials also supports only modest retreat (rather than collapse) during MIS 5e and MIS 9, restricting sea-level contributions from the Wilkes Subglacial Basin to a maximum of ~0.5–1 metres at those times (Sutter et al., 2020; Crotti et al., 2022). MIS5e ice sheet modelling further suggests localised glacier acceleration and thinning enhanced inland erosion, coeval with sedimentary records (Wilson et al., 2018), with insufficient atmospheric warming given the known topography boundary conditions to allow ocean-driven inland retreat (Golledge et al., 2021).

Near-future changes are likely in the marine basins of Antarctica, due to their vulnerability to ocean-driven basal melting and run-away grounding line retreat. However, each catchment has a different sensitivity to climate and ocean forcing (Golledge et al., 2017a). New direct glaciological combined with geological evidence of past ice-sheet behaviour and regional ocean dynamics are needed to inform tipping points and thresholds on a sector-by-sector basis.

2.3.4 The Bipolar Seesaw and Atmosphere-Ocean-Ice Sheet Interactions in the Late Pleistocene

The bipolar seesaw invokes the interhemispheric redistribution of atmospheric and oceanic heat on centennial to millennial timescales via changes in the AMOC (Stocker and Johnsen, 2003) to explain the anti-phase temperature patterns observed in Greenland and Antarctic ice cores (Blunier et al., 1998; EPICA Community Members, 2006). In this hypothesis, a strong AMOC causes warming in the North Atlantic and cooling in the SO, whereas a collapse of AMOC and reduced

North Atlantic Deep Water formation leads to cooling in the North Atlantic and warming in the SO (Broecker, 1998; Stocker and Johnsen, 2003). The forcing generating this seesaw could originate from processes affecting deep-water formation in both the North Atlantic and/or the SO, while both oceanic and atmospheric processes probably played a role in transmitting such signals (WAIS Project Members, 2015; Buizert et al., 2018). In the case of a weakened AMOC, the build-up of ocean heat north of the ACC is transferred poleward across the ACC via eddies to Antarctica, which melts sea ice and sets up the ice-albedo feedback that results in further warming (Pedro et al., 2018). SO observations today show warming and freshening trends around the Antarctic margin (Bronselaer et al., 2020), impacting SO overturning circulation (Figure 2.4).

The bipolar seesaw can cause significant local warming of the ocean and the atmosphere in the vicinity of Antarctica that is above the expected 'background' levels for a given climate state (Holden et al., 2010), which could help explain peak Pleistocene interglacial Antarctic temperatures that were ~2–4°C warmer than pre-industrial conditions (Marino et al., 2015). Such warming could be crucial for driving both atmospheric and ocean mechanisms that influence ice-sheet stability (Clark et al., 2020). For example, Antarctic ice loss during early MIS 5e has been proposed during and/or following Heinrich Stadial 11 when the AMOC was perturbed by freshwater released by Northern Hemisphere ice sheets (Rohling et al., 2019; Turney et al., 2020; Figure 2.5), and several other climate states such as the last deglaciation (Golledge et al., 2014; Weber et al., 2014). The bipolar seesaw can act as a positive feedback mechanism for Antarctic ice mass loss, whereby enhanced upper-ocean stratification around Antarctica and southward shifts in Southern Hemisphere westerly winds (Menviel et al., 2018) arise in response to weakening of the AMOC, enhancing upwelling and incursions of warm CDW onto and across Antarctic continental shelves (Fogwill et al., 2014) and reducing AABW formation and abyssal ocean ventilation (Phipps et al., 2016; Figure 2.6). Such wind shifts have been observed over recent decades (Herraiz-Borreguero et al., 2022). The resemblance between processes that operated during MIS 5e and those characterising the present-day or near future suggests that inter-hemispheric coupling could play a major role in regulating the future of the Antarctic system.

These processes are consistent with those captured in recent observations and modelled outcomes for future ice-ocean feedbacks and AABW formation (Silvano et al., 2018; Bronsalear et al., 2018; Figure 2.5c–e). Furthermore, there is also evidence for AMOC instability within other recent interglacial periods (e.g., MIS 11; Galaasen et al., 2020; Glasscock et al., 2020), which suggests that it may be a persistent feature of the climate system, and one that could reoccur in the future. Current ice sheet simulations are typically run until 2100 (e.g., Golledge et al., 2019), preventing a full assessment of how bipolar seesaw mechanisms will impact Antarctic contributions to sea-level rise in the coming centuries.

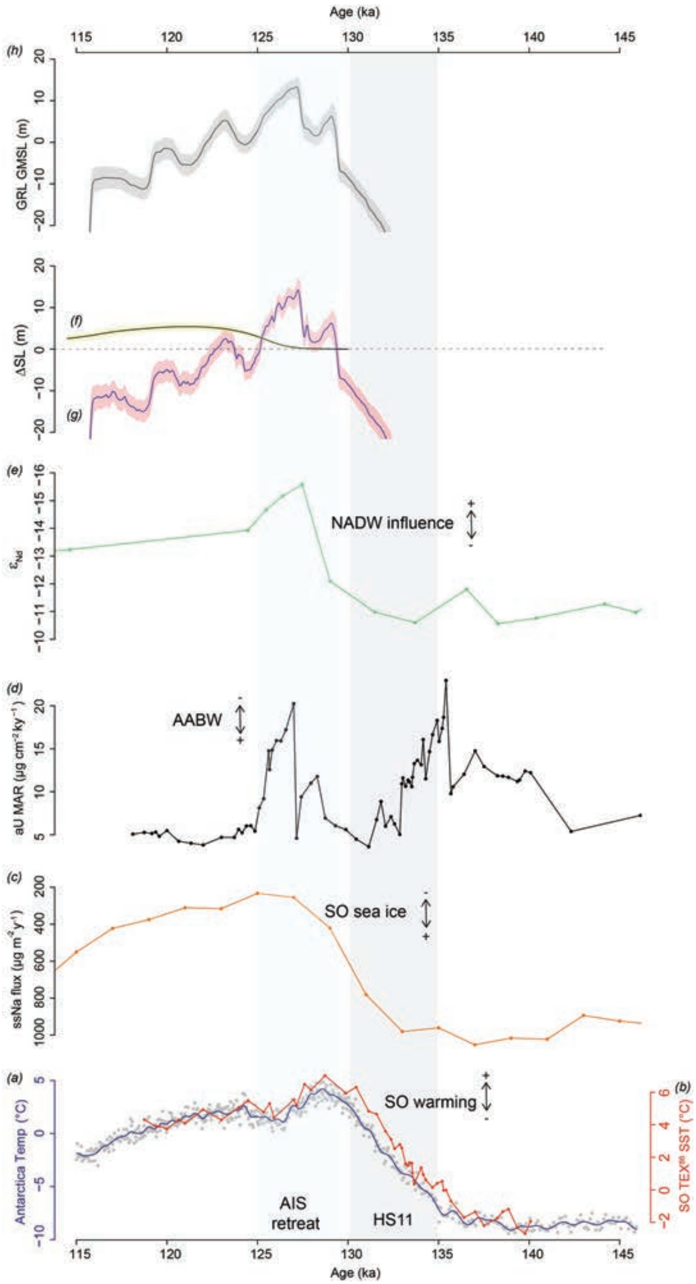

FIGURE 2.4 The Antarctic Ice Sheet contribution to MIS 5e sea-level rise following Heinrich Stadial 11 (130–135 ka). (a) Antarctic air temperature (Jouzel et al., 2007), (b) Southern Ocean $TEX_{86}{}^{L}$ sea-surface temperature (Hayes et al., 2014), (c) Antarctic sea-ice extent inferred from sea salt sodium flux (ssNa) (Wolff et al., 2006), (d) authigenic U accumulation rate at ODP Site 1094 in the Southern Ocean (Hayes et al., 2014), (e) Nd isotopic composition tracing AMOC changes from ODP Site 1063 on the Bermuda Rise, NW Atlantic (Deaney et al., 2017), (f) Greenland Ice Sheet contribution to global sea level from the model-data assimilation of Yau et al. (2016), (g) AIS contribution to sea-level rise based on the difference between (h) the Red Sea KL11 global sea-level record and the Greenland sea-level contribution (Rohling et al., 2019). Shading shows 95% confidence intervals.

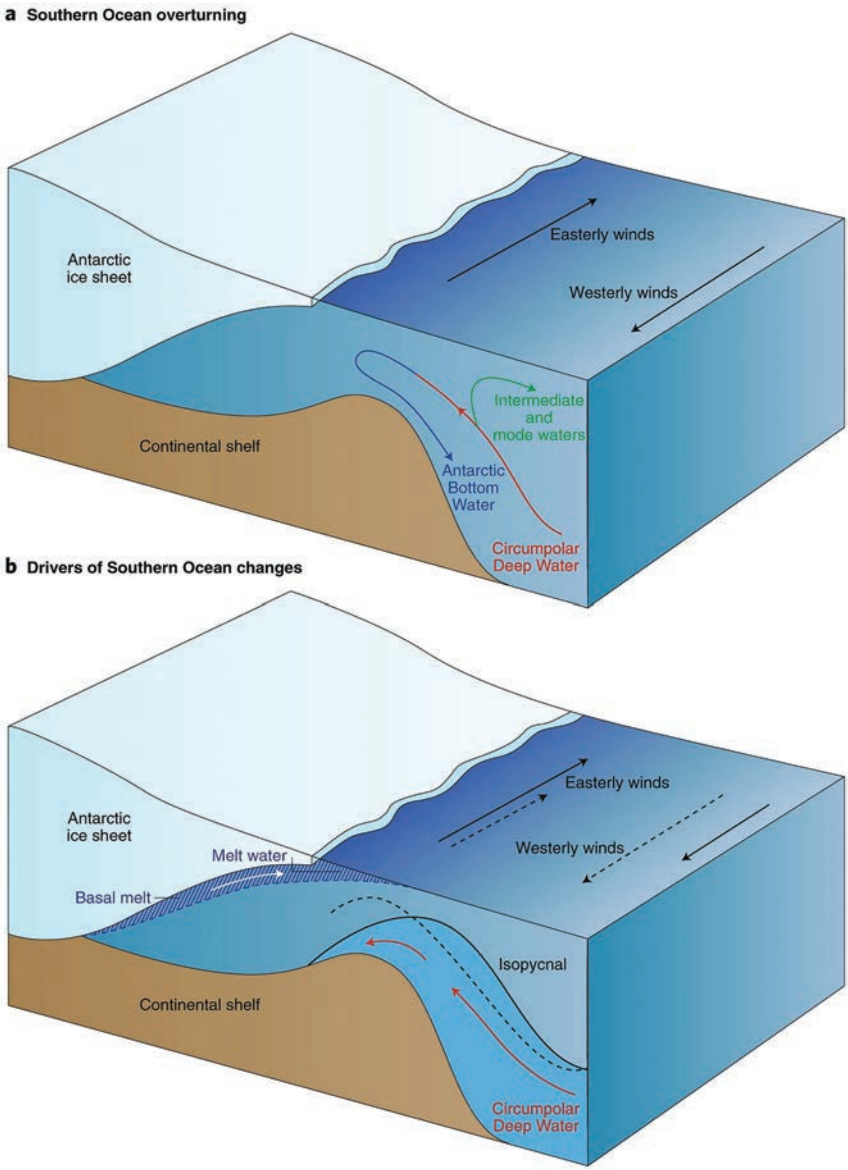

FIGURE 2.5 (a) Present-day conditions in the Southern Ocean showing the divergence between westerly and easterly winds that drives upwelling of CDW, which is transformed into either lighter intermediate and mode waters (upper overturning) or denser AABW (lower overturning); (b) A strengthening and poleward shift of westerly winds, combined with weaker easterly winds (dashed arrows; Bronselaer et al., 2020), causes isopycnals to shoal near the Antarctica, driving more warm water intrusions onto the continental shelf (dashed line). Increased meltwater discharge from the AIS enhances ocean stratification near the surface (figure from Silvano, 2020).

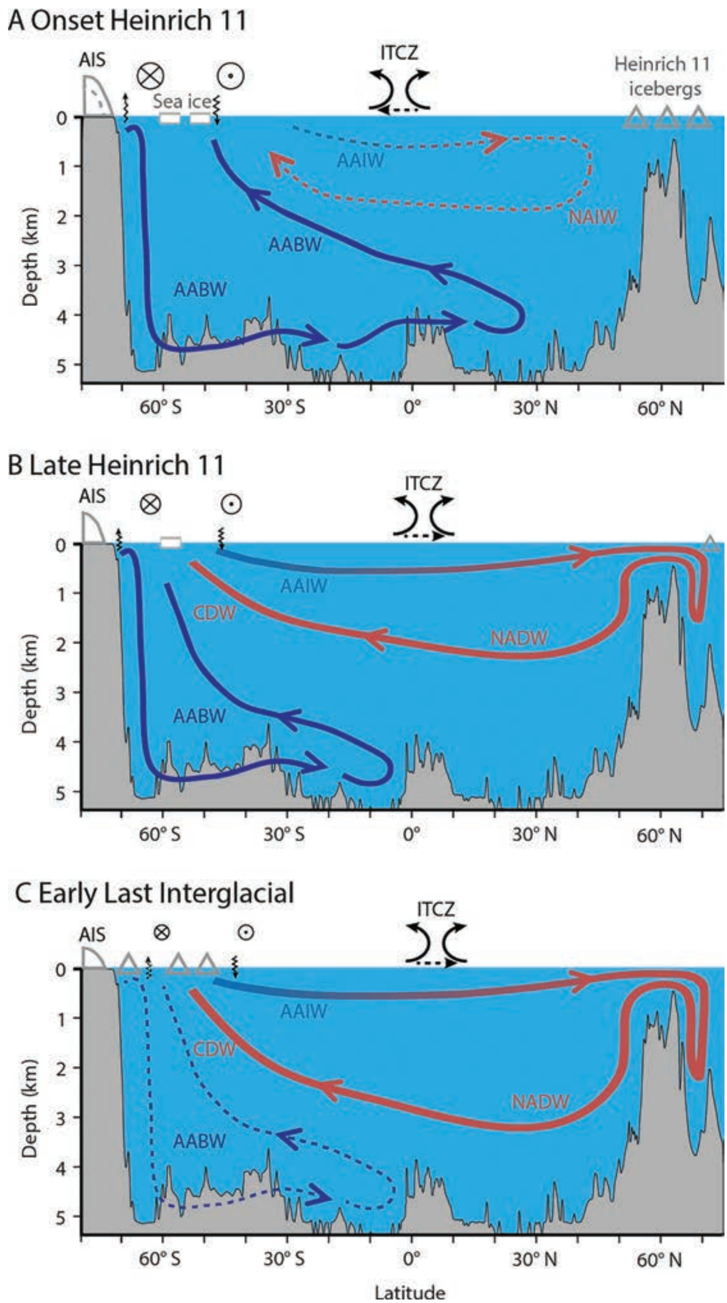

FIGURE 2.6 The bipolar seesaw at the end of the penultimate glaciation 130–135 ka ago, showing the change in AABW formation in response to iceberg discharge (Heinrich stadial 11) in the North Atlantic, which disrupted the AMOC (A–B) and resulted in a build-up of heat in the Southern Hemisphere. (C) Ice core evidence shows substantial ice mass loss from the Weddell Sea sector of Antarctica in response to ocean heat transfer via CDW to the Antarctic margin during the Last Interglacial (figure modified from Turney et al., 2020).

2.4 Summary and Future Directions

The geological record provides observations of the Antarctic Ice Sheet (AIS) and SO during remarkably different climate settings and over a range of timescales. These observations provide constraints for modelling studies to test our understanding of the processes that are relevant to predictions of future Antarctic and SO change. The processes and rates governing AIS mass loss continue to contribute large uncertainties to future sea-level rise projections (Oppenheimer et al., 2019). These processes include those governing ice dynamics, such as marine ice cliff instability and hydrofracturing, the role of subglacial hydrology/hydrogeology, the solid-Earth response to changes in ice mass and feedbacks associated with meltwater and sea ice that can act to moderate oceanic and atmospheric warming.

Ice-sheet growth and retreat since the establishment of the AIS around 40 Ma has increased the extent of interaction between the ice sheet and the ocean. This vulnerability developed through repeated erosion of the Antarctic continent during warm periods across the Oligocene and Miocene, resulting in low-lying topography in West Antarctica and large subglacial basins in East Antarctica (e.g., Wilkes Basin, Aurora Basin; Figure 2.2). The growth of continental shelves and associated expansion of the ice sheet as the climate cooled during the Plio-Pleistocene modified the interaction of the AIS with the ocean. Glacial expansion of the ice sheet calved deep troughs seaward, which today, under modified atmospheric and oceanic conditions, help to facilitate the cross-shelf transport of CDW to the grounding lines of glaciers draining low-lying basins (e.g., Thwaites and Pine Island Glaciers).

Paleo-archives from the Mid-Miocene Climate Optimum, with peaks in atmospheric CO_2 of ~800 ppm (CenCO2PIP Consortium et al., 2023), provide insight into the worst-case SSP5–8.5 future climates, with some differences due to the modern ice sheet being more sensitive to ocean forcing and runaway retreat than for the more stable Miocene Antarctic topography. The CO_2 forcing of the Mid-Pliocene Warm Period (367 ppm; de la Vega et al., 2000) has already been surpassed today. However, the warm Mid-Pliocene provides insight into an equilibrated climate state with smaller ice sheets associated with more southerly SO SST gradients and reduced sea ice relative to present. More recent warm interglacial periods of the Pleistocene, particularly MIS 11 and MIS 5e, experienced strong SO heat build-up associated with the collapse of AMOC and are likely the best short-term (centennial to millennial scale) analogues to current and future anthropogenic climate forcing.

Further international collaboration is necessary across the Antarctic-SO science community to develop new geological archives to understand which vulnerable sectors of Antarctica will contribute to sea-level rise in the near-term, the regional climate and solid-Earth thresholds associated with atmospheric and oceanic forcing, and estimates of the rate of ice sheet change. Other feedbacks requiring further research include the impact of changes in sea ice and meltwater on wider SO ecosystems and climate feedbacks related to changes in the global overturning circulation system.

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3

GLOBAL ATMOSPHERIC INFLUENCE ON ANTARCTICA

Xichen Li, David M. Holland, and Cunde Xiao

3.1 Introduction

A series of changes have been observed over the Antarctic in the past several decades, including rapid warming, accelerated glacier melting in West Antarctica and the Antarctic Peninsula, and fluctuating sea ice levels. Until 2015, most of the Southern Ocean around Antarctica experienced increased sea ice extent, except in the Amundsen and Bellingshausen Seas (Figure 0.1), followed by a sudden sea-ice retreat. These changes are largely attributed to the forcing of the global atmosphere. Stratospheric ozone loss has been identified as a key driver, while the rising greenhouse gas (GHG) concentrations also play an important role. While the radiative forcing from increased GHGs may warm the Antarctic surface, the stratospheric ozone loss intensifies the Southern Annular Mode (SAM), the leading mode of Southern Hemisphere atmospheric circulation. This shift in circulation largely contributes to temperature and sea ice changes through atmospheric thermal advection and mechanical forcing.

Changes in the Antarctic climate also display strong zonal asymmetry, with the most pronounced changes occurring in West Antarctica and the Antarctic Peninsula (Figure 0.1). Atmospheric teleconnections, driven by tropical ocean variability, are critical in driving these asymmetric changes. Recent studies suggest that teleconnections, influenced by a negative Interdecadal Pacific Oscillation (IPO) and a positive Atlantic Multidecadal Oscillation (AMO), have significantly contributed to observed changes. These insights are crucial for predicting whether these driving forces will persist in the future.

This chapter reviews the global atmosphere's impact on Antarctica, examining the relative importance of atmospheric teleconnections versus GHG increases and ozone dynamics in driving recent Antarctic changes. We also explore future

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advancements in Antarctic observation systems, dynamical models, and the potential role of artificial intelligence (AI) in Antarctic climate research.

3.2 Antarctic Changes under Global Warming

The global mean surface temperature (GMST) has risen by approximately 1°C since 1850–1900, with an accelerated increase since 1981 (IPCC, 2021; NOAA, 2022). GMST is projected to continue rising until at least mid-century, regardless of emissions scenarios (IPCC, 2021). This global warming is largely driven by the increased concentration of GHGs, especially carbon dioxide (CO2), which has surged by nearly 50% since preindustrial times, reaching 414 ppm in 2020 (Kumar, 2018; Keeling et al., 2021; Graven, 2021). Feedback mechanisms, such as ocean heat uptake, further contribute to warming (Frölicher et al., 2013). While some atmospheric aerosols, like sulfates and nitrates, exert a cooling effect, others, including black and brown carbon, enhance warming (Nazarenko et al., 2017; Bond et al., 2013).

The increase in GMST is not uniform, with land areas warming more than oceans and the most significant warming occurring at high latitudes in the Northern Hemisphere (Hansen et al., 2006). Notably, Arctic temperatures are rising 2–3 times faster than the global average (Figure 3.1), a phenomenon known as Arctic amplification, which is most pronounced in fall and winter (Taylor et al., 2013; You et al., 2021; Previdi et al., 2021). In contrast, Antarctic climate change presents a more complex picture. The surface air temperature (SAT) trends over Antarctica among different reanalysis datasets exhibit considerable diversity (Figure 3.1), indicating significant uncertainty in the estimated SAT trends for Antarctica. According to in-situ observations from Antarctic stations, a distinct east-west asymmetry exists in SAT trends: West Antarctica and the Antarctic Peninsula are experiencing rapid warming, while changes in East Antarctica are not statistically significant (Bromwich et al., 2012; Steig et al., 2009; Nicolas et al., 2014; Bromwich, 2014). The warming trend in the Antarctic Peninsula has stalled since the late 1990s (Turner et al., 2016). Unlike the Arctic, Antarctic sea ice has not declined since the late 1970s, showing an overall positive trend until a sharp decrease began in 2016, particularly in the Weddell and Ross Seas (Parkinson et al., 2012; Cavalieri, 2012; Turner et al., 2015; Turner et al., 2009; Parkinson, 2019; Turner et al., 2017).

The observed Antarctic climate changes, including surface warming and sea ice variability, are linked to human-induced stratospheric ozone depletion and increased GHGs (Dalaiden et al., 2022; Haumann et al., 2014). Ice and snow albedo feedback also influence sea ice, with initial expansion driven by albedo effects later reversed by significant losses in 2016–2018 (Riihelä et al., 2021). Black carbon deposition from human activities exacerbates warming by darkening snow and ice surfaces, accelerating melting. This effect has reduced snow cover in the Antarctic Peninsula by 23 mm of water equivalent per summer (Bond et al., 2013; Cereceda-Balic et al., 2020; Kang et al., 2020; Cordero et al., 2022).

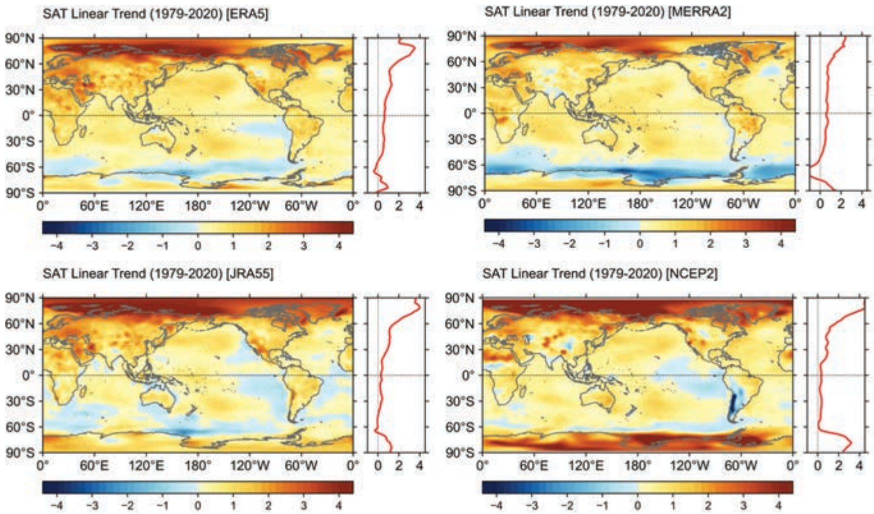

FIGURE 3.1 Linear trend of annual mean surface air temperature (SAT) from 1979 to 2020 based on four reanalysis datasets. The Arctic exhibits the most pronounced trends in SAT. However, given the large diversity among the four datasets, the uncertainty in the SAT trend for Antarctica is higher compared to other regions globally.

While anthropogenic factors like GHGs, ozone depletion, and aerosols contribute to Antarctic warming and sea ice loss, the observed east-west asymmetry suggests that these alone cannot explain the complex patterns of change. Large-scale atmospheric circulation adjustments and teleconnections from lower latitudes are also likely influencing these variations, which will be explored in subsequent sections.

3.3 Large-Scale Atmospheric Circulation Contributions to Antarctic Climate

3.3.1 Southern Annular Mode, Ozone Depletion, and Greenhouse Gas Increase

The SAM is a key driver of Antarctic climate variability, significantly influencing Southern Hemisphere atmospheric circulation (Fogt and Marshall, 2020). The SAM index measures its strength and temporal variations. Most often it is defined as the first principal component of anomalous geopotential height (Rogers and Van Loon, 1982; Marshall, 2003). Positive SAM (Figure 3.2) phases are characterized by intensified westerly winds near 60°S and a poleward shift of the polar jet stream, often coupled with a deepening of the Amundsen Sea Low (ASL), highlighting the asymmetric nature of the SAM (Figure 3.2) (Raphael et al., 2016; Turner et al., 2013).

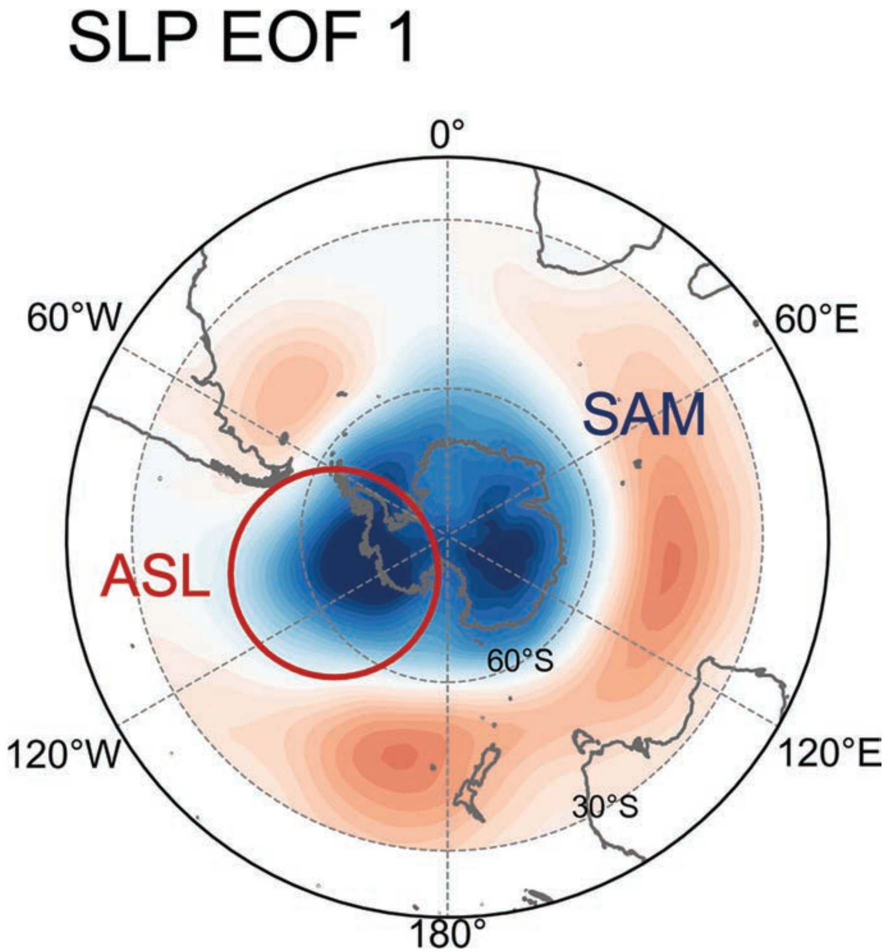

FIGURE 3.2 Spatial pattern of the Southern Annular Mode (SAM), defined as the first EOF of the sea level pressure over the Southern Hemisphere. The Amundsen Sea Low (ASL) serves as one of the three low-pressure centres of the SAM.

The SAM experienced a pronounced positive trend during the austral summer (DJF) in the late 20th century, accompanied by a strengthening of the polar jet. These circulation changes are closely linked to stratospheric ozone depletion, as well as increased GHG concentrations (Arblaster and Meehl, 2006; Thompson et al., 2011, Abram et al., 2014; Dennison et al., 2015; Fogt et al., 2017). Significant stratospheric ozone loss in October, exceeding 50% compared to pre-ozone depletion levels, has led to stratospheric cooling and a strengthened stratospheric jet during spring, with effects propagating to the troposphere and influencing the SAM in summer (Thompson et al., 2011; Thompson and Solomon, 2002).

In addition to ozone depletion, rising GHG levels contribute to the positive SAM trend by amplifying the temperature gradient from mid to high latitudes, strengthening the circumpolar westerlies in accordance with thermal wind balance theory (Fogt and Marshall, 2020). While GHGs impact the SAM year-round, their influence is generally weaker than that of ozone depletion, particularly in summer (Arblaster and Meehl, 2006; Polvani et al., 2011; Gerber and Son, 2014). Solar variability, modulated by the Quasi-Biennial Oscillation, also correlates with the SAM (Roy and Haigh, 2010).

3.3.2 Southern Annular Mode Contributions to the Observed Antarctic Climate Changes

The positive trend of the SAM significantly influences the Antarctic climate, particularly during the austral summer, affecting temperature, sea ice, precipitation, and oceanic changes in the Southern Ocean (Thompson and Solomon, 2002). The Antarctic Peninsula experienced rapid summer warming from the 1970s to the early 2000s, while East Antarctica surface temperature trends were mostly insignificant during the same period (Thompson and Solomon, 2002). Nearly half of the Peninsula's warming and most of East Antarctica's cooling until the early 2000s are attributed to the positive SAM trend in summer (Thompson and Solomon, 2002; Thompson et al., 2011). The mechanisms driving warming on the Peninsula vary: in the east, foehn winds from strengthened circumpolar westerlies drive warming, while in the west, northerly winds along the deepened ASL are more influential (Clem and Fogt, 2013; Fogt and Marshall, 2020).

Precipitation patterns over Antarctica are also closely tied to the SAM (Marshall et al., 2017; Turner et al., 2019). Positive SAM phases generally reduce precipitation inland, but the deepened ASL associated with the SAM enhances moisture transport from the Southern Ocean to the western Antarctic Peninsula, increasing precipitation there. In contrast, the eastern Peninsula experiences reduced precipitation due to a rain shadow effect created by the region's high mountain ranges, which obstruct moisture advection (Fogt and Marshall, 2020).

The SAM also affects the Southern Ocean and Antarctic sea ice through changes in near-surface winds (Holland and Kwok, 2012; Lefebvre and Goosse, 2005; Fogt and Marshall, 2020). Strengthened circumpolar westerlies, influenced by the SAM, are crucial for the Southern Ocean upwelling and have been linked to the weakening of carbon sinks in the Southern Ocean over recent decades (Le Quéré et al., 2007). During summer, positive SAM trends contribute to the observed warming and freshening of the subsurface Southern Ocean and a poleward shift of the frontal zones associated with the Antarctic Circumpolar Current (ACC) (Thompson et al., 2011) (Chapter 4).

3.3.3 Effect of the Ozone Recovery

Since the start of the 21st century, the implementation of the Montreal Protocol has effectively curbed the production and consumption of ozone-depleting substances, leading to the recovery of the Antarctic ozone layer (Banerjee et al., 2020; Sofieva et al., 2017; Weber et al., 2018; Zambri et al., 2021). This recovery, particularly evident in September, has been confirmed by both observation (Weber et al., 2018) and reanalysis datasets (Zambri et al., 2021). Multi-model projections suggest that midlatitude lower stratospheric ozone in the Southern Hemisphere will return to 1980 levels by around 2055 (Eyring et al., 2010).

However, significant uncertainties remain due to the large year-to-year dynamical variability in total ozone, which can obscure recent trends (Weber et al., 2018). This variability underscores the importance of accounting for natural influences when assessing ozone recovery.

Ozone recovery since 2001 has reversed the trends in stratospheric temperature and circulation seen during the ozone hole period (Zambri et al., 2021). As a key heat source, stratospheric ozone's recovery has led to significant warming in the Antarctic stratosphere and has weakened the polar vortex (Zambri et al., 2021). Beyond the stratosphere, ozone recovery impacts the troposphere and Southern Hemisphere surface climate, particularly the SAM. Recent studies show that the positive SAM trend and the poleward shift of the mid-latitude jet during austral summer (DJF) have paused or slightly reversed due to ozone recovery linked to the Montreal Protocol (Banerjee et al., 2020; Zambri et al., 2021). Numerical simulations also suggest that ozone recovery will mitigate Antarctic sea ice loss in the first half of the 21st century (Smith et al., 2012) and may cool the Southern Ocean surface, potentially increasing Antarctic sea ice due to cloud radiative effects. However, observational evidence supporting these predictions remains limited.

3.4 Tropical-Polar Teleconnections Impact Antarctic Climate

The SAM plays a significant role in the climate variations and changes over Antarctica. However, the circulation changes associated with the SAM may not fully explain the asymmetric patterns of Antarctic climate changes. Recent studies suggest that these seasonal and regional variations may be influenced by anomalous atmospheric circulation triggered by teleconnections from the tropics.

3.4.1 Tropical-Polar Teleconnections Influence Antarctic Climate Variabilities

The El Niño/Southern Oscillation (ENSO) is the most influential mode of tropical climate variability, with strong interannual variations that affect global climate, including the Southern Hemisphere. ENSO-related disturbances propagate to higher latitudes via atmospheric and oceanic pathways, impacting Antarctica.

A key teleconnection mechanism in the Southern Hemisphere is the stationary Rossby Wave, generated by tropical convection due to anomalous surface heating (Karoly, 1989; Mo and Higgins, 1998). This wave train, known as the Pacific-South

America (PSA) pattern (Figure 3.3), is a dominant circulation feature in the region (Mo and Higgins, 1998). ENSO-driven tropical signals reach Antarctica through the South Pacific, extending from the Ross Sea to the Bellingshausen Sea, where the semi-permanent ASL is located (Fogt et al., 2012; Turner et al., 2013; Hosking et al., 2013; Raphael et al., 2016). During El Niño events, the PSA pattern features an anomalous low-pressure center east of New Zealand, a high-pressure anomaly near the ASL, and a low-pressure center over South America and the South Atlantic (Figure 3.3). La Niña events reverse this pattern. The PSA pattern also disrupts the mean zonal flow over the South Pacific (Sinclair, 1996; Renwick, 1998).

These teleconnection processes extend beyond ENSO to include other tropical-polar connections. For example, convective heating in the Indian Ocean Dipole or the tropical Atlantic and North Atlantic can also generate Rossby wave trains (Cai et al., 2011; Nuncio and Yuan, 2015; Li et al., 2014; Simpkins et al., 2014). These mechanisms operate across various timescales. On intra-seasonal scales, Rossby waves excited by Madden-Julian Oscillations can reach the southern high latitudes within days to weeks, affecting temperature and sea ice (Pohl et al., 2010; Yoo et al., 2012; Flatau and Kim, 2013). On multidecadal scales, Rossby wave trains from the tropical and North Atlantic significantly influence the surface climate of the southern high latitudes (Li et al., 2014; Simpkins et al., 2014). The warming observed in the Antarctic Peninsula and West Antarctica over recent decades is linked to decadal to multidecadal changes in tropical ocean sea surface temperatures (SST) via the Rossby wave mechanism (Ding et al., 2011, 2012; Schneider et al., 2012b; Clem and Fogt, 2015; Schneider et al., 2015; Meehl et al., 2016).

3.4.2 Teleconnections on Multidecadal Time Scales

Tropical-polar teleconnections on multidecadal scales contribute to observed changes in the Antarctic climate system. The ASL has deepened across all seasons in recent decades, partially reflecting the positive SAM trend and linking to the IPO and the AMO (Turner et al., 2009; Fogt and Wovrosh, 2014; Ding et al., 2012; Meehl et al., 2016). These decadal SST modes influence Antarctic climate via the Rossby wave mechanism (Figure 3.3), with effects persisting for decades, though their spatial anomalies differ from those associated with ENSO (Clem and Fogt, 2015).

The IPO anomaly pattern shows a stronger meridional gradient and zonal asymmetry compared to ENSO. During the negative IPO phase, convection in the South Pacific Convergence Zone generates a Rossby wave train (Figure 3.3), creating a low-pressure anomaly over the Drake Passage (Figure 0.1; Turner et al., 2016). These IPO teleconnections, induced by cooling in the central and eastern equatorial Pacific—similar to La Niña but peaking in austral autumn—lead to deepening of the ASL. Conversely, central Pacific warming weakens the ASL (Ding et al., 2011). Similar decadal teleconnections from the Atlantic, driven by AMO changes,

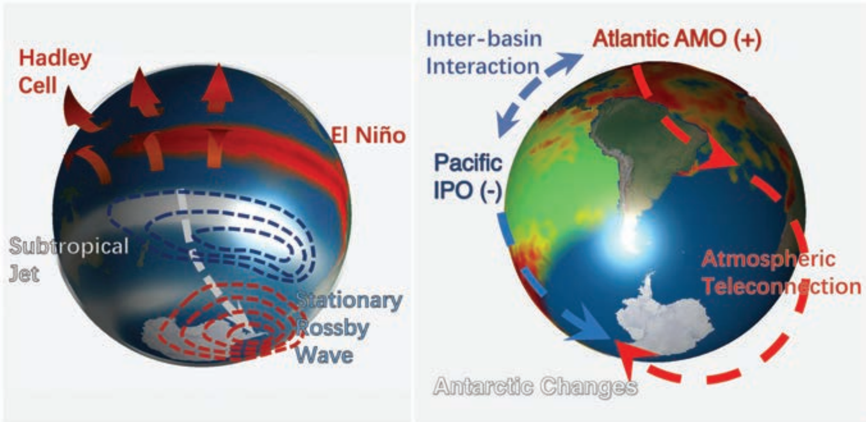

FIGURE 3.3 Schematic Figure of Tropical-Antarctic teleconnections on interannual and decadal time scales. (a) Tropical sea surface warming intensifies the Hadley circulation, interacting with subtropical jet and generating the stationary Rossby wave train, propagating to the polar region. (b) Both Atlantic and Pacific decadal variabilities may have contributed to the Antarctic climate changes in recent decades.

generate a Rossby wave train along the Southern Ocean (Figure 3.3), influencing ASL deepening, especially during austral winter when the subtropical jet's role is stronger (Li et al., 2014; Simpkins et al., 2014).

Both the AMO and the IPO affect Southern Hemisphere atmospheric circulation variability. The AMO predominantly deepened the ASL before 2000 as it transitioned from a negative to a positive phase, while the IPO became more influential after the late 1990s when it entered a negative phase (Simpkins et al., 2014). These tropical teleconnections impact not only atmospheric circulation but also the Southern Ocean, Antarctic sea ice, and ice sheets, as discussed in the following sections.

3.4.3 Teleconnections Contribute to Multi-spherical Changes

Tropical-polar teleconnections significantly influence multi-spherical changes in the Antarctic climate system, including ocean temperatures, sea ice, and the Antarctic Ice Sheet (AIS). These teleconnections play a crucial role in shaping the complex interactions within these systems.

The Southern Ocean, located north of the ACC, has warmed in the upper 2000 meters since the 1950s (Gille, 2002). This warming is driven by increased ocean heat uptake in the Southern Hemisphere, with regional sea level trends mirroring the rise in ocean heat content. Key factors include changes in local surface heat forcing, equatorward Ekman transport, and the intensification of the super-gyre circulation (Cai et al., 2010) (Chapter 4). The positive trend of the SAM, influenced by rising CO2 levels and Antarctic ozone depletion, also contributes. Studies suggest this SAM trend is further affected by remote tropical ocean variability, such as the positive phase of the AMO (Li et al., 2014; Simpkins et al., 2014).

South of the ACC, surface waters have slightly cooled, but continental shelf waters in the Amundsen and Bellingshausen Seas have warmed, accelerating ice shelf melting in West Antarctica (Fan et al., 2014). Circumpolar deep water (CDW) has warmed at most longitudes (Figure 3.4), while Antarctic Bottom Water (AABW) has warmed and freshened, linked to atmospheric circulation changes driven by tropical teleconnections, regional ocean-ice shelf interactions, and wave and advective processes (Masuda et al., 2010; Johnson et al., 2014; van Wijk and Rintoul, 2014) (Chapter 4).

Antarctic Sea Ice. Despite global warming, the Antarctic sea ice extent has slightly increased since the late 1970s, contrasting with the significant decline in Arctic sea ice (Turner et al., 2009). This increase varies seasonally, with the strongest growth in austral summer and autumn. However, regional variations are notable (Figure 3.4): sea ice extent has decreased in the Amundsen and Bellingshausen Seas, while it has increased in the Weddell and western Ross Seas, and along the Oates coast (Figure 0.1; Jacobs and Comiso 1997; Hobbs et al., 2016). These regional changes also affect the timing of ice advance and retreat, with later advances and earlier retreats in the Amundsen and Bellingshausen Seas, and the opposite pattern in the Ross Sea (Stammerjohn et al., 2012) (Chapter 6).

The contrasting regional changes in Antarctic sea ice are driven by multiple factors. Variability in atmospheric circulation at middle and high latitudes, including the SAM, the ASL, and zonal wave three patterns, significantly influences these changes (Yuan and Li, 2008; Ding et al., 2012). Tropical mechanisms also play a role, particularly in interannual and regional variability. During La Niña events, a deepened ASL increases sea ice west of the Ross Sea and decreases it in the Amundsen, Bellingshausen, and Weddell Seas, forming the Antarctic sea ice dipole (Simmonds and Jack, 1995; Kwok and Comiso, 2002). On longer timescales, teleconnections from a negative IPO phase and a positive AMO phase have influenced recent sea ice distribution (Simpkins et al., 2014, 2016; Li et al., 2014).

Antarctic Land Ice. In recent decades, the AIS has experienced rapid melting, characterized by accelerated land ice loss and an asymmetry between West and East Antarctica (Pritchard et al., 2012; Shepherd et al., 2018). From 1992 to 2017, the ice sheet lost approximately 2720 ± 1390 Gt of ice, with the most significant losses in West Antarctica and the Antarctic Peninsula, particularly at Pine Island Glacier, Thwaites Glacier, and Larsen B and C ice shelves (Figures 0.1 and 3.4) (Steig et al., 2012; Jenkins et al., 2018). In contrast, East Antarctica has shown minimal ice loss or even slight accumulation, except for the Totten Glacier (Figure 0.1), whose melting rate increased rapidly in the past 15 years.

Since the modern satellite era began in 1979, significant atmospheric circulation changes, including an intensified SAM and deepened ASL, have impacted Antarctic land ice. These changes alter surface wind stress, driving ocean circulation and Ekman pumping anomalies that facilitate the intrusion of warm CDW towards the ice front, accelerating glacier melting (Schmidtko et al., 2014; Shepherd et al., 2018). Tropical-polar teleconnections also contribute by redistributing sea ice, particularly during intensified ASL winters, leading to sea-ice loss in the Weddell Sea and exposing land ice to ocean swells, which has contributed to the break-up of Larsen B and C ice shelves (Hellmer et al., 2012).

Additionally, these atmospheric changes have caused rapid warming in West Antarctica through thermal advection from lower latitudes (Figure 3.4), while East Antarctica has experienced weaker cooling (Simpkins et al., 2014). This warming accelerates surface melting and increases basal sliding (Zwally et al., 2002). Teleconnection-induced anomalies also alter precipitation patterns, impacting snow accumulation and ice sheet thickness, particularly during El Niño years when melting exceeds accumulation, resulting in a net mass loss (Paolo et al., 2018).

Overall, the observed atmospheric circulation changes associated with tropical-polar teleconnections have profound implications for the Antarctic climate system. These changes impact glacier melting, sea ice distribution, regional warming patterns, and precipitation dynamics. Understanding these mechanisms is crucial for accurately assessing the future stability of the AIS and its implications for global sea level rise.

3.5 Atmospheric Influence on Antarctica in the Future Climate System

The future projection of Antarctica's climate is a critical concern, especially considering that more than half of the global population resides in coastal regions (Parish et al., 1994). However, the accuracy of Antarctic climate projections is challenged by limited observational data and the sparse distribution of measuring stations. Consequently, significant uncertainties persist in our understanding of Antarctic climate dynamics. To address limited observational data, reanalysis data (Bromwich et al., 2011; Palerme et al., 2017) and global climate models (GCMs) (Agosta et al., 2015) are utilized for spatiotemporal climatological records, improving future climate projection for Antarctica. However, significant inter-model variability and uncertainties exist in climate projections for the region.

3.5.1 Future Projection of the Atmosphere around Antarctica

Projections based on CMIP5 and CMIP6 simulations under various scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5, SSP1–2.6, SSP2–4.5, SSP3–7.0, SSP5–8.5) indicate that by the end of the 21st century, Antarctic temperatures could rise by 1–4°C, with greater warming in interior regions than coastal areas (Palerme et al.,

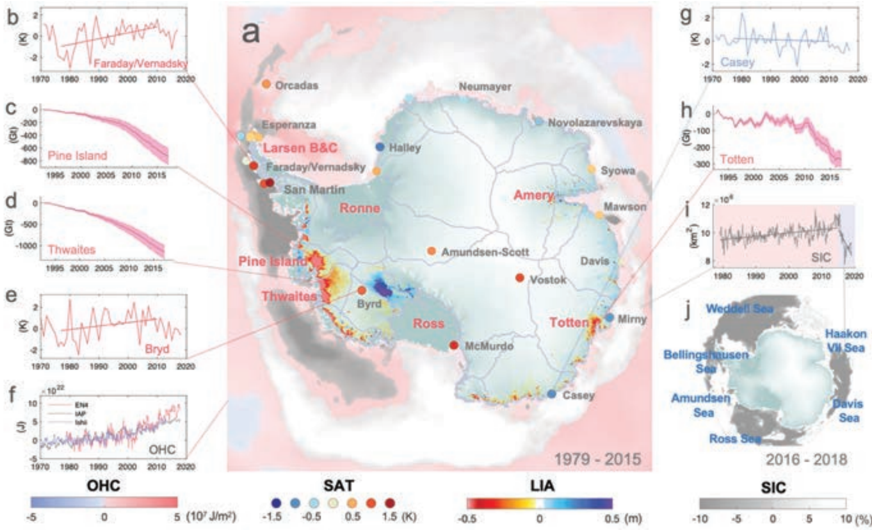

FIGURE 3.4 Observed climate changes around Antarctica associated with teleconnection and atmospheric circulation changes. (a) Spatial patterns of a series of climate changes around Antarctica, including ice-sheet elevation change (color shading around the coastal area) from 1992 to 2017, surface air temperature (SAT) changes observed by Antarctic weather stations (colored dots over the Antarctic continent) from 1979 to 2015, sea ice concentration changes (white–gray mapping around Antarctica) from 1979 to 2015, and ocean heat content changes above 1500 meters (red and blue colors over the ocean) from 1979 to 2015. b, e, and g show time series of SAT observed at Faraday/Vernadsky station (Figure 0.1) (b), Byrd station (Figure 0.1) (e), and Casey station (Figure 0.1) (g), representing the Antarctic Peninsula, West Antarctica, and the coastal area of East Antarctica, respectively. c, d, and h show the evolution of ice mass anomaly for three of the fastest-thinning glaciers, Pine Island Glacier (c), Thwaites Glacier (d), and Totten Glacier (h), respectively. (f) Evolution of the Southern Ocean heat content anomaly above 1500 meters from three independent estimations (EN4 as red curve, IAP as black curve, and Ishii as blue curve). (i) time series of the total sea ice area. The Antarctic sea ice experienced a slow increase up to 2015, followed by a sudden loss in 2016. (j) Spatial pattern of this sea ice loss (2016–2018) (white–gray colors).

2017; Bracegirdle et al., 2020; Tewari et al., 2022; IPCC AR6, 2021). This uniform warming across seasons underscores the potential consequences for Antarctic ecosystems, ice sheets, and global sea levels.

Surface temperature changes in Antarctica are strongly linked to the SAM, particularly in austral summer. The SAM index has shown a robust positive trend since 1970, mainly due to stratospheric ozone depletion and, to a lesser extent, increased GHGs (IPCC AR6, 2021). Future SAM trends will be influenced by ozone recovery and continued GHG emissions. The IPCC AR5 projects a weakening of the positive SAM trend in summer and autumn as ozone recovers by mid-century, though SAM trends in other seasons depend on emission scenarios. Higher emissions could lead to a more pronounced positive SAM trend (Gillett and Fyfe, 2013; Solomon and Polvani, 2016). CMIP5 models suggest a weak negative SAM trend under RCP2.6 and RCP4.5 in summer, but a weak positive trend under RCP8.5. CMIP6 models predict a more positive SAM in summer under SSP3–7.0 and SSP5–8.5 scenarios, with the most significant changes in winter, where a nearly 5 hPa increase in the SAM index is projected under SSP5–8.5 (IPCC AR6, 2021).

CMIP5 experiments suggest that ASL will deepen in all seasons except summer under increasing radiative forcing (Raphael et al., 2016). CMIP6 models project a likely deepening of the ASL across all seasons, with larger amplitudes under warming scenarios from 1.5°C to 4°C above pre-industrial levels (Gao et al., 2021). The ASL is expected to enhance and shift poleward during the Ross-Sea sea ice advance season, highlighting the significant impacts of future climate change on the ASL and the Antarctic region.

3.5.2 Future Projection of the Southern Ocean and Antarctic Sea Ice

The Southern Ocean is projected to continue warming due to rising CO2 levels. CMIP5 models indicate that warming trends will persist, with temperatures increasing by 1°C–3°C by 2100 under RCP4.5 and RCP8.5 scenarios, primarily in the upper ocean (Sallée et al., 2013). AABW is also expected to warm by up to 0.3°C under RCP8.5. Concurrently, the upper ocean is projected to freshen, with a salinity decrease of approximately 0.1, leading to increased stratification and shallower mixed layers, which could impact the Atlantic meridional overturning circulation (AMOC) (Rintoul, 2018).

CMIP6 models, as detailed in the IPCC AR6 report, predict further warming throughout the Southern Ocean, with an average increase of 0.62°C by 2100 under SSP245 and SSP585 scenarios (Purich and England, 2021). Warming is expected to concentrate in deep pools north of the Subantarctic Front, consistent with observed trends over the past 50 years, though uncertainties remain (Armour et al., 2016; Cai et al., 2023). These uncertainties stem from factors such as climate sensitivity, interactions between the ocean, atmosphere, and cryosphere, Antarctic ozone recovery, and oceanic eddy representation (Cai et al., 2023).

Warming of the Southern Ocean is linked to increased sea ice loss, although models often struggle to simulate this accurately. The IPCC AR6 report did not highlight Antarctic sea ice loss projections due to low confidence, largely because of the Antarctic sea-ice paradox—where sea ice increased before 2015 despite global warming (IPCC AR6, 2021). However, recent studies suggest that under strong forcing scenarios, up to 50% of the Southern Ocean's sea ice area could disappear during winter by 2100 (Roach et al., 2020; Holmes et al., 2022). These findings underscore the need for improved models to better project Antarctic sea ice dynamics.

3.5.3 Future Projection of the Antarctic Ice Sheet

AIS melting plays a crucial role in future sea-level rise. According to dynamic ice sheet models, if no policy changes are implemented, there could be a rapid increase in global sea levels of 0.5 cm per year from Antarctica after approximately 2060 (DeConto et al., 2021). Incorporating ice cliff failure in the model, under the RCP8.5 scenario, it is estimated that the AIS could contribute 1.05±0.30 m by 2100 and increase to 15.65±2.00 m by 2500. However, revised projections suggest a likely contribution of 0.45 m by 2100 if the mechanism proposed by DeConto and Pollard (2016) is valid (Edwards et al., 2019).

For a high emission scenario, the West Antarctic Ice Sheet (WAIS) is projected to contribute 0.03 to 0.46 m by 2100, increasing to 0.07 to 2.2 m by 2300. On the other hand, the East Antarctic Ice Sheet (EAIS) may contribute −0.04 to 0.11 m by 2100 and increase to −0.14 to 0.51 m by 2300 (Bamber et al., 2019). These projections highlight the potential significant impact of the AIS melting on future sea-level rise and emphasize the importance of implementing effective policies and mitigating climate change to minimize the associated risks.

However, the impact of enhanced precipitation resulting from climate changes on sea-level rise is found to be partially counteracting (Frieler et al., 2015). Projections from climate models indicate a significant increase in Antarctic precipitation during the 21st century (Vignon et al., 2021), with a seasonal dependency that favors greater increases in winter compared to summer (Turner et al., 2014). It is suggested that the number of intense precipitation events near the ice sheet domes and ridges, particularly in East Antarctica, will increase (Krinner et al., 2007). However, projections of precipitation from GCMs exhibit notable uncertainties, with a wide range of relative changes for the Antarctic continent under the RCP8.5 scenario in both CMIP5 (1.8% to 43%, Palerme et al., 2017) and CMIP6 (Roussel et al., 2020). These uncertainties stem from the low resolutions and the lack of polar-specific physics in the models, resulting in discrepancies in capturing the mean value, trend, and seasonality of different variables over Antarctica. These biases and discrepancies pose a significant challenge in making reliable climate change projections for the region.

3.5.4 Projection of the Antarctic–Global Climate Interaction

Ongoing GHG emissions are expected to continue driving warming in Antarctica and the Southern Ocean, leading to increased precipitation, ice sheet melting, changes in sea ice, intensified poleward westerly winds, and impacts on polar ecosystems. Antarctica's ice mass directly affects global sea levels, while differential warming between the Southern and Northern Hemisphere oceans creates energy imbalances that influence cross-equatorial Hadley circulation and ocean circulation (Singh et al., 2016; Schneider et al., 2018; Cai et al., 2023). Changes in vertical salinity and heat transport between the surface and deep Southern Ocean impact global overturning circulation, AABW formation, subpolar gyres, and the ACC (Ohshima et al., 2013). These processes are influenced by global warming, atmospheric circulation variability, such as the SAM (Wang et al., 2019) and the ASL (Hosking et al., 2016), and internal variability, with potential teleconnections from tropical regions (Meehl et al., 2019; Li et al., 2021).

Anthropogenic warming is also projected to alter tropical climate patterns, particularly through a slowdown of the Pacific Walker circulation, leading to faster warming in the eastern Pacific (Xie et al., 2010). This El Niño-like shift can generate stationary Rossby wave trains, weakening the ASL and causing negative sea ice anomalies in the Ross Sea, positive anomalies in the Amundsen and Bellingshausen Seas, and increased ice sheet accumulation in West Antarctica (Paolo et al., 2018).

Future changes in tropical Atlantic SST can also impact Southern Hemisphere high latitudes, either directly or through Pacific interactions (Nuncio and Yuan, 2015; Li et al., 2016). Variations in Atlantic SST, including shifts in the AMO, can affect the Hadley circulation and subtropical jet stream, influencing Rossby wave propagation to the Amundsen-Bellingshausen Seas and impacting the ASL and SAM (Li et al., 2014; Simpkins et al., 2014; Li et al., 2015; Simpkins et al., 2016). Additionally, a weakening AMOC due to global warming may deepen the ASL (Orihuela-Pinto et al., 2022).

Teleconnections influencing Antarctica may be further modified by changes in background atmospheric circulation. Strong links have been established between Southern Ocean warming and ENSO events (England et al., 2020; Kang et al., 2020; Wang et al., 2022). Southern Ocean warming reduces heat absorption, leading to a decline in Antarctic sea ice extent and increased heat accumulation in low latitudes, particularly in the eastern equatorial Pacific, which accelerates warming (England et al., 2020). This intensifies ENSO variability by enhancing atmospheric convection and promoting El Niño events (Cai et al., 2018). Elevated ENSO intensity, driven by increased CO2 emissions, can further influence Southern Ocean warming by modifying southern high-latitude winds (Wang et al., 2022; Cai et al., 2023).

3.6 Future Directions

Investigating climate change in Antarctica is challenging due to harsh conditions and limited observations, hindering our understanding of atmospheric influences on the region. For instance, Antarctica lost approximately 2,720 billion tons of ice from 1992 to 2017, contributing over 7 mm to global sea level rise (Shepherd et al., 2018). However, discrepancies among observation sources introduce significant uncertainties, sometimes accounting for half of the observed changes. Additionally, studying warm water intrusion and ocean wave effects on ice shelf melting requires long-term, high-resolution observations of sub-surface ocean temperatures and land ice movements, which are currently scarce.

Recent advancements, such as polar-orbiting satellites, Argo floats, autonomous underwater vehicles, and automatic weather stations, have improved monitoring of Antarctica. Image recognition and machine learning techniques are also enhancing evaluations of land ice flow and mass flux near ice fronts. Despite these advances, an integrated, long-lasting dataset combining satellite, ship, Argo float, and ground-based observations is urgently needed. This would enable systematic studies of Antarctic climate variability and its interactions with the Southern Hemisphere's atmospheric system.

Climate models are crucial for compensating for observational limitations and enhancing our understanding of Antarctic climate mechanisms. However, improvements are still needed. For instance, ice shelf-ocean interactions have only recently been included in models, essential for accurately assessing future sea level rise. Many physical processes, such as ice shelf calving and CDW intrusion, remain poorly represented due to coarse resolution or inadequate parameterizations. Biases also persist in simulating the polar atmosphere's mean flow and the tropical Pacific's state and variability, with many models exhibiting a cold tongue bias and failing to capture ENSO diversity. Improving models within a fully interactive Earth system framework, incorporating high-resolution atmosphere, ocean, and ice components, is essential. Moreover, improving the accuracy of sea ice projections is crucial, as current climate models struggle to simulate sea ice changes accurately.

AI has shown promise in polar science (Liu, 2021). Beyond direct forecasting, AI can enhance traditional polar forecast systems. For instance, random forest algorithms have been used to calibrate Arctic sea ice drift forecasts (Palerme and Müller, 2021). AI technologies also excel in detecting and tracking moving objects in remote sensing, such as iceberg detection (Krishnan et al., 2022) and monitoring the Antarctic coastline (Heidler et al., 2021). AI's potential to optimize model parameterizations and perform quality control makes it a key tool for advancing polar forecast systems.

3.7 Summary

Antarctica has experienced significant changes in recent decades, including rapid warming, glacier melting, and fluctuating sea ice, particularly in West Antarctica and the Antarctic Peninsula. These changes are largely driven by global atmospheric forcings, such as stratospheric ozone depletion and rising GHG concentrations, which have intensified the SAM and ASL, leading to shifts in atmospheric circulation. These shifts have resulted in temperature and sea ice variability through atmospheric thermal advection and mechanical forcing. Additionally, atmospheric teleconnections triggered by tropical ocean variability, such as those linked to the IPO and AMO, play crucial roles in driving the observed asymmetric climate changes across Antarctica, shaping the complex interactions within its climate system.

According to Coupled Model Intercomparison Project (CMIP) models, temperatures in Antarctica are projected to rise by 1–4°C by the end of the 21st century, with significant impacts on ecosystems, ice sheets, and global sea levels. However, considerable uncertainty remains in these projections due to the lack of observations and the relatively poor performance of numerical models around Antarctica. This highlights the need for a more comprehensive observational system, advanced climate models, and a deeper understanding of Antarctic climate dynamics. While new technologies, including polar-orbiting satellites, Argo floats, and AI, have improved our understanding, challenges remain in integrating diverse data sources into comprehensive, long-term datasets. Improved climate models that accurately represent key processes, such as ice shelf-ocean interactions and atmospheric circulation, are essential for better predicting future changes and their global implications. AI offers promising advancements in model calibration, data analysis, and remote sensing, enhancing our ability to project and manage the impacts of Antarctic climate change.

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4

SOUTHERN OCEAN CIRCULATION

Global Drivers and Ongoing Changes

Jean-Baptiste Sallée, Adele K. Morrison, Kaitlin Naughten, and Andrew F. Thompson

4.1 Introduction

Nearly one-third of the planet's oceanic surface is located in the Southern Ocean encircling the Antarctic continent south of 30°S (Figure 0.1). This immense oceanic expanse is unique in many ways and exerts a significant influence on global ocean circulation and the planet's climate. The Southern Ocean is subject to the planet's most intense winds and hosts the most energetic current on Earth, the Antarctic Circumpolar Current (ACC). During winter, a large part of its surface is covered by sea ice, providing a refuge for unique fauna and supporting biodiversity. The Southern Ocean is in contact with the vast Antarctic glaciers that flow onto its surface for hundreds or thousands of kilometres. This unique and hostile climatic environment influences the structure of a global ocean circulation that connects all ocean depths from the surface to the abyss and links the Pacific, Atlantic, and Indian ocean basins. The circulation in the Southern Ocean plays a crucial role in heat and carbon exchange between the atmosphere and the ocean, as well as redistributing worldwide a large amount of vital life-supporting tracers, such as nutrients and oxygen.

The horizontal circulation of the Southern Ocean is dominated by the strong ACC, which flows uninterrupted from west to east in the mid-latitudes (Figure 4.1). South of the ACC, two main subpolar cyclonic gyres create a buffer between the ACC and the Antarctic continental margin in the Ross and Weddell Seas (Figure 4.1). The circulation along the fringe of the Antarctic continental shelf is dominated by the Antarctic Slope Current (ASC), generally flowing from east to west, along much of the Antarctic continental slope. The horizontal circulation is closely coupled to a vertical overturning circulation, associated with the formation and consumption of various water masses, creating a three-dimensional circulation

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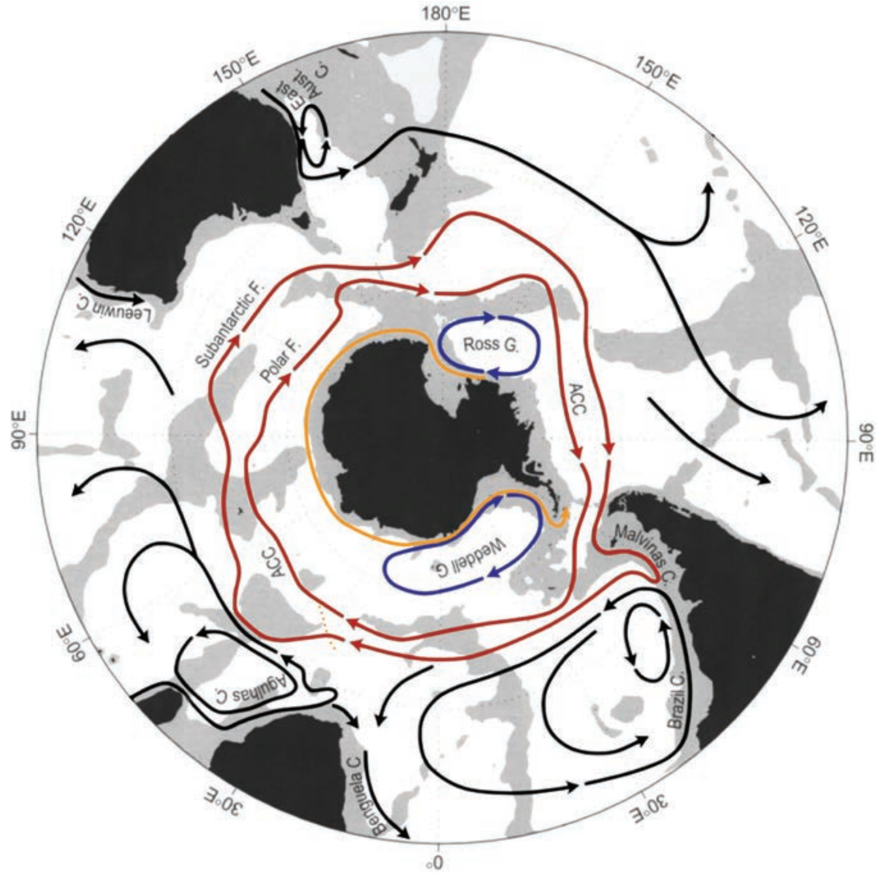

FIGURE 4.1 Schematic map of major currents in the southern hemisphere oceans south of 20°S. Depths shallower than 3500 m are shaded in gray. The two major cores of the Antarctic Circumpolar Current are shown in red, the Subantarctic Front and Polar Front. The two main subpolar gyres, the Ross and Weddell Gyres, are shown in blue. The Antarctic Slope Current is shown in orange. Abbreviations used are F for front, C for Current and G for gyre. Adapted from Rintoul et al. (2001).

system (Figure 4.2). Water masses are parcels of water of common origin with distinct temperature, salinity, and density ranges (Figure 4.2a), which can become "transformed" into different classes, through processes such as surface forcing, interaction with sea ice and ice shelves, or interior mixing. This water mass transformation is at the heart of the Southern Ocean's overturning circulation, a double-cell structure which replenishes, or transfers, surface-sourced tracers into the ocean interior (DeVries et al., 2011; Marshall & Speer, 2012; Sallée et al., 2010). This transfer is known as ventilation.

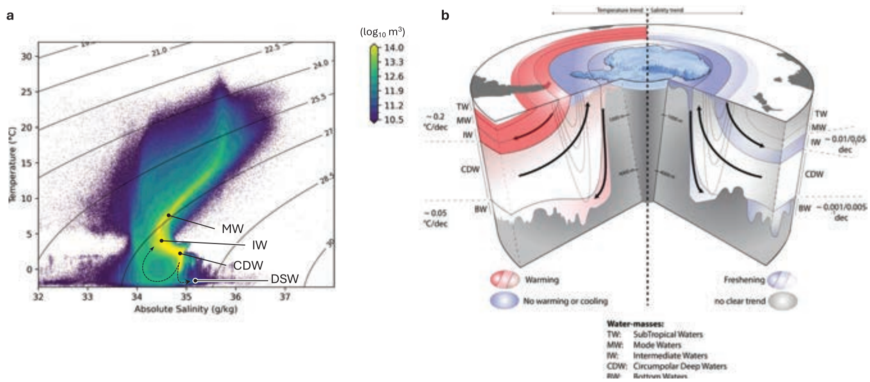

FIGURE 4.2 (a) Southern Ocean (<30°S) upper ocean (<2000 m) temperature/salinity volumetric water mass census (in units of m^3, plotted as log volume of each 0.01 °C by 0.01 g/kg temperature/salinity bin) estimated from the IAP (Institute of Atmospheric Physics, Chinese Academy of Sciences) reconstruction from years 2000 to 2022 (Cheng et al., 2017). Selected water masses are labelled: mode waters (MW), intermediate water (IW), Circumpolar Deep Water (CDW) and Dense Shelf Waters (DSW). The black dashed arrow shows the main surface closing of the overturning circulation, connecting the upwelled CDW with the IW and MW through a "cold water transit", as well as connecting the upwelled CDW with DSW. (b) Schematic showing temperature and salinity trends in different layers of the Southern Ocean. The layers are defined as the main water masses of the Southern Ocean: subtropical water (TW), mode water (MW), intermediate water (IW), Circumpolar Deep Water (CDW) and bottom water (BW). Black arrows show the main overturning pathways in the basin, and the dashed black contours show a vertical slice of the deep-reaching Antarctic Circumpolar Current circulating clockwise around the Antarctic continent. Adapted from Sallée (2018).

Observed changes in Southern Ocean water masses and associated changes in Southern Ocean circulation have the potential for widespread climate implications within this century, making them highly relevant to politics and society. Due to its vertical circulation pattern and because a large range of densities rise up towards and outcrop at its surface, the Southern Ocean is disproportionately effective at absorbing and sequestering anthropogenic heat (Frölicher et al., 2015; Zanna et al., 2019). The surface temperature of the Southern Ocean, which is influenced by the delicate balance of overturning strength, upper ocean stratification, and sea ice cover, plays a significant role in cloud feedback and has been identified as a key regulator of global temperature (Kang et al., 2023). In fact, it is one of the primary factors determining the timing at which the global warming threshold of 2°C will be reached for a given emission scenario (Shin et al., 2023).

Changes in the strength of the upper overturning cell circulation can impact the ocean's capacity to absorb excess heat and carbon resulting from human activities and distort the global redistribution of nutrient fluxes (Sarmiento et al., 2004). A reduction in the strength of the lower overturning cell can delay the exceedance of global atmospheric warming targets, 1.5°C or 2°C, by more than a decade (Bronselaer et al., 2018). Decreases in the abyssal overturning can also disrupt global precipitation patterns by enhancing drying in the Southern Hemisphere, increasing precipitation in the Northern Hemisphere (Bronselaer et al., 2018), and reducing the efficiency of the global ocean carbon sink (Liu et al., 2023). The warming and potential change in the circulation of the subpolar Circumpolar Deep Water (CDW) due to increased upper ocean stratification can intensify the basal melt of Antarctic ice shelves, thereby destabilising them and leading to significant global sea level rise (Li et al., 2023; Silvano et al., 2018).

In this chapter, we review some recent advances in our understanding of the processes that drive and change the circulation and water masses of the Southern Ocean. In Section 4.2, we begin by providing a detailed account of the circulation and its drivers, including the dynamics of the circulation and the formation and transformation of associated water masses. Moving on to Section 4.3, we describe the observed changes and projected future changes, and their drivers. Finally, we conclude the chapter in Section 4.4.

4.2 Southern Ocean Circulation: Three-Dimensional Structure and Drivers

4.2.1 ACC and the Upper Cell of the Overturning Circulation

The ACC connects the Atlantic, Pacific, and Indian basins, thus enabling a truly global circulation (Figure 4.1). The eastward flow of the ACC is divided into a series of narrow jets that are among the strongest currents in the ocean and also give rise to coherent ocean vortices, or eddies, that are responsible for intense mixing in regions where ACC jets interact with major bathymetric features of the seafloor (Thompson & Sallee, 2012). Because of these processes, the ACC not only connects different ocean basins but also effectively blends waters from these disparate regions and contributes to setting global distributions of heat, nutrients, and dissolved gas concentrations.

The circulation of the ACC derives its energy from both mechanical and thermodynamical sources, or from surface wind and buoyancy forcing, respectively. The ACC largely coincides with the latitudes of the Southern Hemisphere westerlies. As the westerlies are aligned with the eastward flow of the ACC, they provide a source of kinetic energy to the surface ocean. The winds also generate a near-surface, frictionally balanced equatorward transport, known as Ekman transport, that is linearly proportional to the magnitude of the surface wind stress, creating upward pumping south of the ACC and downward pumping north of the ACC. This pattern of "upwelling" and "downwelling" on the flanks of the ACC has important consequences for the stratification within the ACC by tilting density surfaces away from horizontal, rising towards the surface as they stretch from north to south across the ACC (Marshall & Speer, 2012). This tilting is also a source of potential energy in the system, which is readily converted to kinetic energy through a hydrodynamic instability known as baroclinic instability. Baroclinic instability fuels the formation of mesoscale eddies that support the intense mixing of the Southern Ocean. Modelling studies have also shown that the total surface buoyancy forcing can also influence the strength of the ACC by modifying the upper ocean density distribution (Shi et al., 2020).

In addition to the flow of waters around Antarctica, the ACC also supports a secondary, overturning circulation that is roughly ten times weaker than the eastward flow of the ACC (in terms of volume transport) but is critical for the transfer of heat, carbon, and nutrients northward and southward across the ACC (Figure 4.2). The tilted density surfaces within the ACC provide a pathway for deep ocean waters to rise up towards the surface while remaining roughly along the same density surfaces (Marshall & Speer, 2012). Similarly, waters at the surface can be subducted along density surfaces flowing into lower latitudes at intermediate depths (Morrison et al., 2022; Sallée et al., 2010). Thus, the ACC's density structure and overturning circulation influence how waters fill the deep ocean (Purkey et al. 2018), how nutrients are delivered to low latitudes (Sarmiento et al., 2004), how heat is delivered to the Antarctic ice shelves (Tamsitt et al., 2017), and how older water masses are brought back to the surface and exchange dissolved gasses with the atmosphere (Morrison et al., 2022).

In a two-dimensional, depth-latitude framework, the Southern Ocean overturning is dominated by "upper" and "lower" cells, while in reality, it has a complex three-dimensional structure (Tamsitt et al. 2017) (Figure 4.2). Both the upper and the lower cells of the overturning circulation are fed by warm and salty CDW, which upwells within and south of the ACC (Figure 4.2b). The north-south flow of CDW across the ACC is enabled by eddy motions, which are strongly enhanced downstream of major topographic features (Thompson & Sallee, 2012; Yung et al., 2022). The heavier version of CDW originates from North Atlantic Deep Water, whereas the lighter version of CDW originates from transformed Antarctic Bottom Water (AABW) (Talley, 2013). As CDW reaches the surface, some of it freshens by mixing with sea ice meltwater and precipitation (Pellichero et al., 2018). It flows northward and is transformed into mode water and then intermediate water, which subducts below warmer subtropical water to form the upper cell of the overturning circulation. The transformation of CDW into intermediate water (IW) starts with a transformation into near-surface winter water (WW) via wintertime mixing, and the WW is then warmed to form intermediate water through summertime surface heat fluxes (Figure 4.2a) (Evans et al., 2018). In contrast, another portion of upwelling CDW flows southward to reach the Antarctic continental shelf, where strong sea ice formation causes it to become colder and saltier (Figure 4.2). The result is AABW, the densest class of seawater, which cascades down the continental slope to the bottom of the Southern Ocean to form the lower cell of the overturning circulation. AABW is carried northward along the seafloor into the rest of the world's ocean basins (Purkey et al., 2018; Solodoch et al., 2022).

The sloping density layers that outcrop at the surface in the Southern Ocean provide a connection for atmospheric-sourced tracers, such as oxygen and anthropogenic carbon to penetrate relatively freely into the deeper ocean. A range of processes contribute to ventilation in the Southern Ocean, including convection and turbulence in the upper ocean, large-scale circulation features, such as the overturning and subtropical gyres, and eddy stirring (also known as mixing). The energetic mesoscale eddies of the Southern Ocean stir tracers along density layers, resulting in the downward movement of surface-sourced tracers. This eddy stirring ventilates all depth layers of the Southern Ocean, even transporting tracers downward along upwelling density layers against the opposing upward advection of the overturning circulation (Naveira Garabato et al., 2017). However, the vast majority of the anthropogenic heat and carbon absorbed into the Southern Ocean is advected northward in the thin upper Ekman layer and subducted across the base of the mixed layer on the northern edge of the ACC, filling the mode and intermediate water layers (Armour et al., 2016). Subduction in mode and intermediate layers occurs in a handful of localised hot spots set by the interactions of the meandering ACC with the underlying bathymetry (Sallée et al., 2010). Recent work has highlighted that submesoscale dynamics may also contribute substantially to Southern Ocean ventilation through enhanced deep-reaching vertical velocities and the outcropping of deep-density layers associated with filamentary structures (Bachman & Klocker, 2020; Dove et al., 2021; Siegelman et al., 2020).

4.2.2 ASC, Ice-Shelf Interactions, and the Lower Cell Overturning

Waters that flow across the ACC and continue poleward participate in an intricate circulation system at the Antarctic margins. Above the Antarctic continental slope, relatively warm CDW—a few degrees above the freezing temperature—rises up toward the continental shelf (Figure 4.3). Here, a combination of the shallow shelf bathymetry, surface wind forcing, and water properties of the continental shelf contribute to the formation of the Antarctic Slope Front (ASF; Figure 4.3a). The ASF acts as a key dynamical gateway for the delivery of heat to the ice shelves and the grounding zones of the Antarctic Ice Sheet (AIS), a process that influences global sea level (Fox-Kemper et al., 2021; Thompson et al., 2018). The formation of the ASF has traditionally been attributed to the surface wind forcing (Gill & Niiler, 1973). Around much of Antarctica, the continental shelf break is collocated with a band of easterly (westward) winds that push surface waters onshore in the Ekman layer, establishing a sea surface height gradient that supports a geostrophically-balanced westward flow, the ASC. Similar to the ACC, regions of Ekman convergence and divergence can vertically displace density surfaces that modify the frontal structure of the ASF (Figure 4.3b–d). This has two important implications. First, the density structure determines which water masses have access to the continental shelf. In much of East Antarctica, the density classes that host relatively warm CDW intersect, or incrop, on the continental slope; here, shelf waters are colder, consistent with weaker basal melting of East Antarctic ice shelves (Figure 4.3a). This behaviour is in contrast to West Antarctica, where CDW density classes can flow onto the shelf unimpeded (Figure 4.3a). Second, lateral density gradients at the shelf break lead to vertically-sheared flow in thermal wind balance and can give rise to an "Undercurrent" that flows eastward. In the Amundsen Sea, the strength of the Undercurrent has been tied to the heat content on the continental shelf (Dotto et al., 2020; Wåhlin et al., 2013) as well as ice shelf melt rates on longer time scales (Silvano et al. 2022). Recent studies have also suggested that there is the potential for feedback between coastal processes, e.g. sea ice formation and ice shelf melt, and the ASF through the delivery of modified waters back to the shelf break (Si et al., 2024; Thompson et al., 2020).

Spatial variations in the structure of the ASF are also influenced by the Southern Ocean's subpolar gyres, most notably the Ross and Weddell gyres (Gordon et al., 1981). These features play an important role in both buffering the continental shelf from the ACC's warmer waters but also transporting lighter waters towards the coast and dense waters back to lower latitudes, largely around the gyre periphery. In this way, the subpolar gyres also participate in setting the three-dimensional structure of the Southern Ocean overturning circulation (MacGilchrist et al., 2019; Wilson et al., 2022). Although the subpolar gyres are among the larger circulation features in the Southern Ocean, their size and sea ice cover make them among the more sparsely observed regions and their impact on heat transport and ice shelf melt in a changing climate remains an active area of research (Gómez-Valdivia et al., 2023; Prend et al. 2024). However, recent advances in the processing of satellite altimetry observations now allow their strength, area, and dynamics to be observed from space. These altimetry measurements have led to major progress in our understanding of the subpolar gyres, including their seasonal cycle, drivers, and the associated mesoscale activity (Armitage et al., 2018; Auger et al., 2022, 2023; Dotto et al., 2018).

Over the continental shelf, local water mass characteristics and associated circulation regimes set the rate of ice-shelf melt rates in ice-shelf cavities, the regions of ocean water covered by floating ice shelves. Within these ice-shelf cavities, the ocean transfers heat to the ice shelf, melting ice and increasing the buoyancy of the ocean, which flows back towards the shelf break in lighter density classes. Spatial variations in water masses and in the melting and freezing rates in ice shelf cavities give rise to different conditions around the Antarctic coastline. The continental shelf seas can be broadly categorised into three regimes: fresh shelves, warm shelves, and dense shelves (Moorman et al., 2020; Thompson et al., 2018) (Figure 4.3). These regimes are described, in turn, below.

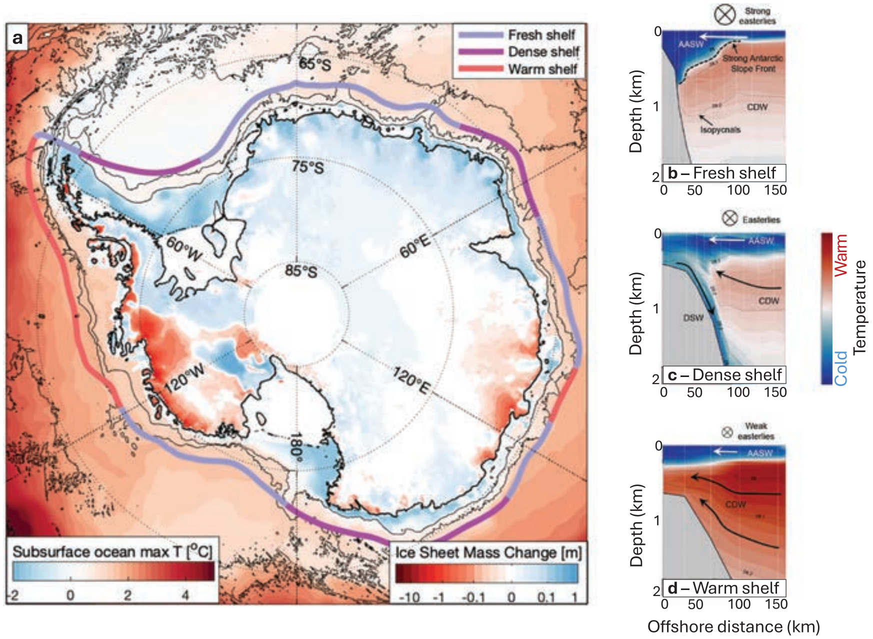

FIGURE 4.3 (a) Oceanic colours show the 2005–2010 mean subsurface ocean potential temperature maximum from the Southern Ocean State Estimate (Mazloff et al., 2010). Black lines indicate isobaths from ETOPO2v2, contoured every 2000 m from the 1000-m isobath; thick black line is the Antarctic continental coast. The thick coloured line parallel to the coast differentiates the three main oceanic shelf regimes (fresh shelf, dense shelf, warm shelf). Continental colours represent ice sheet elevation change (2003–2019), corrected for firn air content to reflect mass change (Smith et al., 2020). (b, c, d) Schematic latitude-depth transects indicating typical winds, subsurface ocean circulation, temperature and density structure in a (b) fresh shelf, (c) dense shelf, and (d) warm shelf regime. Colours represent temperature and black contours isopycnals of neutral density, with the bold black dashed line in (b) indicating the sharp density gradient across the Antarctic Slope Front. Cross-slope circulation is shown schematically with black and white arrows, and wind direction and strength by arrow tails going into the page. Water masses shown include Antarctic Surface Water (AASW), Circumpolar Deep Water (CDW), and Dense Shelf Water (DSW, also referred to as High Salinity Shelf Water in some sectors). Adapted from Stokes et al. (2022)

Fresh shelves. Fresh shelves include the eastern Weddell Sea, the eastern Antarctic Peninsula, and much of East Antarctica (Figure 4.3b). Here, sea ice formation is relatively weak, as is the transport of water onto the shelf from the deep ocean. There is generally minimal presence of either CDW or very dense water masses, and instead, the water column is filled with WW, a cold and relatively fresh water mass near the surface freezing point (−1.9°C).

Warm shelves. Warm continental shelves include the Amundsen and Bellingshausen Seas of West Antarctica, as well as isolated regions of East Antarctica, such as the region surrounding the Totten Ice Shelf (Figure 4.3c). Here, warm and salty CDW flows directly from the subsurface Southern Ocean onto the continental shelf. In some regions, e.g. the West Antarctic Peninsula and Bellingshausen Sea, the CDW is transported onto the continental shelf essentially unmodified, with a temperature of around 1°C (Schulze Chretien et al., 2021). In other regions, slightly cooler modified Circumpolar Deep Water (mCDW) results from mixing with other water masses as they are transported onto the continental shelf. However, even mCDW is warm enough to support substantial ice shelf melting, and warm shelf regions have the highest ice shelf basal melt rates in Antarctica (Adusumilli et al., 2020). Depending on its buoyancy, the admixture of meltwater with ambient ocean then travels westward either within the Antarctic Coastal Current or in the ASC, freshening the regions downstream (Jacobs et al., 2022). Sea ice formation is relatively weak on the warm shelves but causes some water mass transformation during the winter months. As sea ice is formed, the upper layers of the ocean are mixed, and lose their heat to the atmosphere and form WW, which can modulate ice shelf melt rates at interannual timescale (Jenkins et al., 2018; Holland et al., 2022).

Dense shelves. Dense shelves include the Ross Sea, the southwestern Weddell Sea (surrounding the Filchner-Ronne Ice Shelf), Adélie Land, and Cape Darnley near Prydz Bay. These regions are associated with extreme heat loss to the atmosphere, intense CO_2 exchange with the atmosphere, and dense water formation in coastal polynyas, which are regions of open ocean surrounded by sea ice that form due to persistent winds blowing off the ice sheet known as katabatic winds (Williams et al., 2007). Sustained heat loss and associated sea ice formation in the polynyas, lead to the formation of High Salinity Shelf Water (HSSW) that mixes throughout the entire water column, becoming "reset" to the surface freezing point. There is large transport of mCDW onto dense continental shelves from offshore, but its heat is almost entirely lost to the atmosphere by mixing associated with sea ice formation by the time it reaches the ice shelves (Morrison et al., 2020). Instead, ice shelf melting in dense shelf regions may be driven by HSSW (Nicholls et al., 2009). Even though HSSW is at the surface freezing point, it is still warm enough to melt ice shelves at depth, where the freezing point of seawater is lower due to increased pressure. The resulting ice shelf meltwater is supercooled relative to the surface, forming a water mass known as Ice Shelf Water (ISW). Because of their high density, both HSSW and ISW are commonly referred to as Dense Shelf Water, a precursor of AABW.

AABW is the coldest and densest type of water found in the global ocean and is characterized by temperatures below 0°C and neutral densities greater than 28.27 kg/m^3 (Orsi et al., 1999). AABW is formed from Dense Shelf Water, which flows down the continental slope and mixes with surrounding water masses, and ultimately spreads along the ocean bottom. The properties and formation rates of AABW may also be influenced by offshore, open-ocean polynyas, such as those observed in the Weddell Sea during the 1970s, causing convection to depths of up to 3,000 m (Gordon, 1978). However, the primary source region for AABW is the Antarctic continental shelf. AABW originates in localized areas around the Antarctic continent, sinking into the deep ocean and following isobaths on the lower continental slope until redirected northward along deep western boundary currents. AABW is guided topographically through the Southern Ocean, and travels northward in the global ocean abyss along deep western boundary currents, recirculating into the interior of these basins (Orsi et al., 1999). AABW sourced from the Weddell Sea and Prydz Bay are blended and exported together, mainly to the Atlantic and Indian Oceans, while AABW sourced from Adelie Land and the Ross Sea are blended together and exported mainly to the Pacific Ocean (Solodoch et al., 2022). Along this northward trajectory, AABW encounters sills and narrow passages, leading to further modification of its properties through mixing, resulting in increased buoyancy and warmer temperatures (de Lavergne et al., 2016). AABW covers close to 80% of the global seafloor (Purkey et al., 2018). As AABW fills the deep ocean from below, it determines the abyssal ocean stratification, i.e. the change in density with depth, which in turn, regulates the timescale over which heat and carbon can be sequestered in the deep ocean.

4.3 Observed Changes and Outlook in the Future of the Southern Ocean

4.3.1 Large-Scale Warming and Freshening Trends in the Southern Ocean Depths

The Southern Ocean is a major sink of excess heat associated with climate change. Estimates from an observation-based reconstruction suggest that over 1871–2017, the Southern Ocean has accounted for 67% of the global ocean uptake of excess heat (Zanna et al., 2019), and climate models broadly agree with an estimate of ~75% over 1870–1995. This heat is then distributed globally through the overturning circulation (Figure 4.4). The storage of heat that remains in the Southern Ocean south of 30°S in the upper 2000 m is estimated from historical temperature observations to account for 35–43% of the global ocean heat gain since 1970 (Meredith et al., 2019). This proportion has increased in the past two decades (2005–2017) to 45–62% (Meredith et al., 2019).

A large part of this excess heat resides north of and within the ACC (Figure 4.4a), in the mode and intermediate waters layers, which have warmed at a pace of about 0.2°C per decade since 1970 (Figure 4.2b) (Auger et al., 2021; Sallée, 2018). South of Tasmania, a warming of 0.29±0.09°C per decade in these water masses has been estimated from repeated observations; this rate is 2.40 times larger than the typical interannual variability (Auger et al., 2021). The warming is also associated with a freshening of about 0.01–0.05 g/kg per decade (Figure 4.2b) (De Lavergne et al., 2014; Durack & Wijffels, 2010; Fox-Kemper et al., 2021). Freshening and

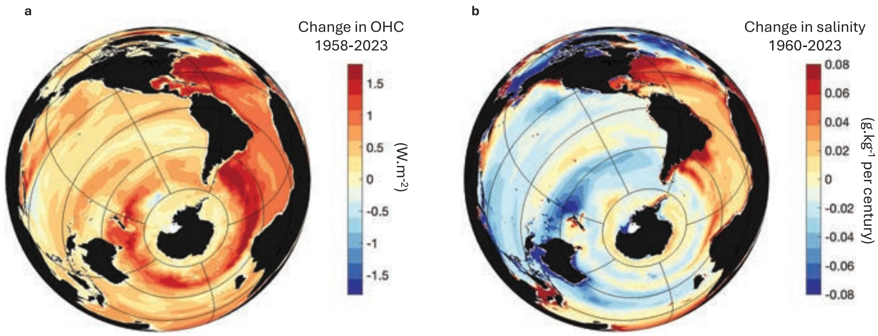

FIGURE 4.4 (a) Ocean heat content (OHC) change from 1958 to 2023 as estimated from a linear trend computed from the IAP reconstruction. (b) Linear trend of ocean salinity averaged over the top 2000 m computed from the IAP reconstruction from years 1960 to 2023 (Cheng et al., 2017, 2020).

warming in these water masses are expected to continue in the future at a rate depending on our future emissions (Silvy et al., 2020, 2022). Changes in mode and intermediate water properties primarily result from changing air-sea-ice fluxes in the subpolar Southern Ocean and within the ACC, and the associated surface hydrographic anomalies are passively subducted north of the ACC with the overturning circulation (Silvy et al., 2022). Decadal-scale variability in the circulation can temporarily accelerate or decelerate these hydrographic changes and thus impact the interpretation of Southern Ocean heat uptake.

In the subpolar Southern Ocean, south of the ACC, the surface layer has slightly cooled and freshened in the past decades (Zhang et al., 2021) (Figure 4.2b, 4.4). The freshening has stratified the upper ocean (Sallée et al., 2021), isolating the relatively warm subsurface water from the cold surface layer and creating favourable conditions for the growth of sea-ice cover. The observed regime changes in sea-ice observed since 2016 is likely to be affecting the long-term trend in surface ocean temperature in the subpolar ocean, with some suggestion of a large surface warming since then (Purich & Doddridge, 2023). The freshwater content change of the subpolar surface ocean is controlled by a combination of changes in the sea-ice growth/melt (Haumann et al., 2016), in ice shelf melt (Jacobs, 2006), and in the atmospheric hydrological cycle (Akhoudas et al., 2023).

Deeper in the water column, the upper part of the CDW layer shows subtle warming, right below the surface layer (Auger et al., 2021; Lecomte et al., 2017; Schmidtko et al., 2014). A repeated expendable bathythermograph (XBT) section of 25 years between Tasmania and Antarctica permitted an estimate of this warming of 0.06±0.02°C per decade, which is 2–4 times greater than the typical interannual variability (Auger et al., 2021). In another study, the warming of this water mass was estimated to be 0.8–2.0°C in 2010–2018 compared to 1930–1990 in the sector 80–160°E (Herraiz-Borreguero & Naveira Garabato, 2022). In addition to the warming of CDW, the depth of the temperature maximum has shoaled at a significant rate that may facilitate the access of warm waters to the Antarctic continental shelf (Auger et al., 2021; Schmidtko et al., 2014).

The abyssal Southern Ocean has also experienced change in the past decades, with a reported AABW volume reduction, warming, and freshening (Purkey & Johnson, 2013; Silvano et al., 2023). These signals appear in all basins of the Southern Ocean (Silvano et al., 2023): the Weddell Sea, East Antarctica, and the Ross Sea, and some of these trends might have regionally accelerated (Purkey et al., 2019). The cause of these changes remains, however, uncertain, with possible drivers including a slowdown in dense water formation (Gunn et al., 2023b; Zhou et al., 2023).

4.3.2 Changes in the Circulation: ACC, Upper Cell, Lower Cell

In contrast to the widespread evidence for warming and freshening trends in the Southern Ocean, observational evidence for circulation changes is scarce, due to the difficulty of measuring circulation directly and the challenge of disentangling trends from variability. Whether or not the ACC has shifted or strengthened over recent decades is still under debate. Some studies have reported a southward shift in the position of ACC fronts (Kim & Orsi, 2014; Sokolov & Rintoul, 2009). However, the detected shift has been shown to be sensitive to the method used to identify frontal locations, and no coherent trend in the position of the ACC is detected when a more accurate definition of fronts is used (Chapman et al., 2020). This absence of frontal movement is consistent with work showing that the path of the ACC is strongly constrained by the underlying bathymetric features (Graham et al., 2012). A regional shift of ACC fronts in regions less constrained by bathymetry, e.g. west of the Kerguelen Plateau, might however be possible according to observed and projected changes (Azarian et al., 2024).

Recently, an acceleration of the eastward flow on the northern edge of the ACC was reported from Argo and satellite observations (Shi et al., 2021). This increase is consistent with modelling work showing that increased buoyancy forcing can drive an acceleration of the ACC (Hogg, 2010; Shi et al., 2020). However, it remains unclear whether the observed acceleration represents a strengthening of the ACC itself or rather a southward shift of the subtropical gyres. This possible sensitivity to buoyancy fluxes is in contrast with the now well documented insensitivity of the ACC zonal transport to changes in the zonal wind stress, a phenomenon referred to as “eddy saturation” (Morrison et al., 2013; Munday et al., 2013).

Observational evidence is limited for long-term trends in the strength of the upper overturning circulation in the Southern Ocean due to the lack of direct circulation measurements and the difficulty of observing such a spatially distributed flow. Indirect reconstructions using an inverse model indicate large decadal variability of up to 50% from one decade to the next (DeVries et al., 2017). Such large variability may obscure any longer-term trends in the upwelling. Observations of chlorofluorocarbons and other tracers of ventilation allow us to compute age changes in different water masses and are suggestive of an enhanced overturning circulation (Ting & Holzer, 2017; Waugh et al., 2013). However, such results need to be interpreted with caution, as there are also other mechanisms that may drive ventilation change, such as eddy stirring, submesoscale activity, subtropical gyre circulations, and upper ocean mixing.

Recent observational evidence indicates that the lower overturning cell transport is weakening. In the Australian Antarctic Basin, AABW transport fed from the Ross Sea and Adelie Land sources has declined by ~30% over the period 1994–2017, driven by meltwater-driven freshening of the source waters (Gunn et al., 2023). In the Weddell Sea, the bottom water volume has reduced by 30% from 1992 to 2020, indicative of a reduced dense water formation rate that would be consistent with an observed wind-driven decline in sea ice formation (Zhou et al., 2023). The decreased northward transport of bottom waters in turn is likely to be driving the observed contraction of the densest waters in the abyssal ocean (Purkey & Johnson, 2012). Similar to the upper overturning, direct observations of the lower overturning cell away from the Antarctic margins are limited.

4.3.3 Continental Shelf and Ice-Shelf Interactions

Ice shelf basal melt is ocean-driven and is the main cause of mass loss from the AIS, which contributes to global sea level rise (Shepherd et al., 2018). Long-term monitoring of ice shelf basal melting across Antarctica began with the advent of satellite missions in the 1990s. A clear increase in basal melting has been observed along the warm continental shelves of West Antarctica, including the Amundsen and Bellingshausen seas (Adusumilli et al., 2020; Paolo et al., 2015), although there is substantial interannual and decadal variability.

Retreat of the West Antarctic Ice Sheet (WAIS) was likely triggered in the 1940s, as determined by analysis of sediment cores from the Amundsen Sea (Smith et al., 2017). This timing corresponds to a strong El Nino event, which is thought to create warm oceanic conditions on the Amundsen Sea causing increased basal melt rates. Smith et al. (2017) hypothesised that if the conditions in the Amundsen Sea were unusually warm in the past, this might have initiated the present thinning of ice.

Model simulations suggest that the Amundsen Sea warmed in response to changes in wind patterns over the 20th century (Gómez-Valdivia et al., 2023; Naughten et al., 2022). Ocean warming would explain why the WAIS failed to recover from a natural climate anomaly, and why increased basal melting continues to the present day (Holland et al., 2022). However, observations of water mass properties on the continental shelf are sparse in both space and time (Schmidtko et al., 2014). The short record of in situ measurements in the Amundsen Sea, combined with large decadal variability, means that significant long-term trends in ocean temperature have not been established in observations.

Ice shelf melting in West Antarctica is determined by the heat content of the CDW layer reaching the continental shelf, which itself can be modulated by the strength of the Amundsen Undercurrent (Naughten et al., 2023). The Undercurrent flows from west to east along the continental slope and transports warm CDW onto the shelf. Variations in the strength of the Undercurrent have been linked to decadal variability in observed melt rates (Jenkins et al., 2016). The first future projections with specialised Amundsen Sea models suggest that ocean warming and increased ice shelf melting will continue over the 21st century, even if global average temperatures stabilise (Jourdain et al., 2022; Naughten et al., 2023), and the continental shelf ocean warming has been attributed to a long-term strengthening of the Undercurrent (Naughten et al., 2022, 2023).

Changes have also been observed in the dense continental shelves, especially in the Ross Sea. A significant freshening trend has been observed in the Ross Sea, where in situ measurements now span six decades (Jacobs et al., 2022). The Ross Sea is directly downstream of the Amundsen Sea so that its freshening has been attributed to the retreat of the WAIS. Freshening of the dense shelves may have the potential to flip these regions to a warm regime (Hellmer et al., 2017; Naughten et al., 2021; Siahaan et al., 2022). HSSW forms a density barrier, which prevents offshore mCDW from reaching the ice shelves. A freshening of the HSSW water mass would weaken the density barrier and could allow warm water to flow directly into the ice-shelf cavities. A larger number of climate projections have focused on the Filchner-Ronne Ice Shelf (FRIS) in the Weddell Sea, showing a potential to abruptly transition to a warm regime (Hazel & Stewart, 2020; Hellmer et al., 2012). Such a transition would dramatically increase FRIS melt rates and potentially cause significant sea level rise. However, it is not clear how easily such a transition could occur, and it may only occur under extreme climate change scenarios, with more moderate forcing causing a slight decrease in basal melting (Naughten et al., 2021; Nicholls, 1997).

4.4 Conclusion

The Southern Ocean stands as a pivotal component of the global climate system, regulating heat, carbon, and nutrient fluxes on a global scale. As we conclude this chapter, it becomes evident that our understanding of its intricate circulation and associated transport processes has advanced significantly in recent years. However, profound uncertainties persist, posing challenges to predicting its future evolution and the consequent impacts on global climate.

Throughout this chapter, we have explored the multifaceted nature of the Southern Ocean circulation, emphasising its three-dimensional structure and the interconnectedness of its water masses. From the powerful ACC to the overturning circulation connecting the surface and the deep ocean, each component plays a vital role in shaping not only regional but also global oceanic and climatic patterns. The frontal structures of the ACC, which arise from a complex interplay between surface wind stress and bathymetry interactions, are a key regulator of the meridional water mass transport. Directly south of the ACC, the subpolar gyres, such as the Ross and Weddell gyres, tend to buffer the continental shelf from the warm CDW. The subpolar gyres influence extends beyond this buffering role, as they participate in setting the three-dimensional structure of the Southern Ocean overturning circulation.

The interaction between warm CDW and the Antarctic continental shelf, moderated by the ASF, determines the ocean heat transfer to the ice shelves and grounding zones of the AIS. The formation of the ASF acts as a dynamic gateway for the delivery of heat and largely determines which water masses have access to the shelf. The presence of lateral density gradients at the shelf break gives rise to vertically-sheared flow, which contributes to the formation of an "Undercurrent" in the West Antarctic region, with implications for heat content and ice shelf melt rates in this region. The combination of these ocean currents and associated water mass transports ultimately determine the distinct characteristics on the Antarctic continental shelf, which can be broadly classified in three main regimes: warm shelf, fresh shelf, and dense shelf.

The water masses of the Southern Ocean have experienced rapid changes in recent decades. The observed large-scale warming and freshening trends result from an intricate interplay between changing air-sea-ice fluxes and the redistribution of heat and freshwater within the ocean. These trends, characterized by increasing heat storage and stratification, have significant implications for regional and global climate dynamics, in particular through the modulation of the sea ice cover and upper ocean temperatures.

Climate projections suggest a future trajectory of the Southern Ocean that includes continued warming, freshening, and changes in circulation patterns. However, significant uncertainties persist, particularly regarding the response of ice shelves and ice-ocean interactions to ongoing climate change. Addressing these uncertainties will require concerted observational and modelling efforts, as well as interdisciplinary collaborations to better understand and anticipate the complex dynamics of the Southern Ocean in a changing climate.

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5

THE SOUTHERN OCEAN COUPLED CARBON AND CLIMATE FEEDBACK LINKS TO THE EARTH SYSTEM

The Present, the Past, and the Future

Pedro M. S. Monteiro, Philip W. Boyd, Judith Hauck, Laurie Menviel, Precious Mongwe, Sarah Nicholson, Sandy Thomalla, and Brian Ward

5.1 Introduction

The Southern Ocean (SO) plays a critical role in the earth's carbon–climate–biogeochemistry nexus through its mediation of both anthropogenic and natural carbon fluxes as well as the earth's energy imbalance and nutrient supplies that support 75% of ocean primary production outside the SO (Sarmiento et al., 2004; Frölicher et al., 2015). In the industrial period, these links are dominated by the two large negative feedback fluxes of the CO_2 sink (±0.75PgCy^{-1}; ±40% of the ocean CO_2 sink: 1985–2018) and heat uptake (±70% of the energy imbalance) (Frölicher et al., 2015; Hauck et al., 2023). The sensitivity and complexity of these strong SO–Earth System (ES) carbon and climate feedback links are emphasized by recent work, which suggests that the elimination of the NH aerosol impact on shortwave radiation may rebalance the magnitudes of the SO carbon and heat sinks (Williams et al., 2024). These two negative feedback fluxes are the core of the strong links between the SO and the ES (Frölicher et al., 2015; Menviel and Spence, 2024).

The SO is linked to the ES through both the relatively fast atmospheric forcing (1–10 years) and the slow (10–100s years) MOC in the ocean, with the mixed layer (ML) as the connection between them (Figure 5.1). Both drive and are influenced by the feedback of CO_2, heat, and wind (Figure 5.1; see Chapters 3 and 4 for atmosphere and ocean physics, respectively). The fluxes link across these three domains and the resulting feedback provides the context to understand and project the past, present, and future role of the SO in the ES (Chikamoto and DiNezio, 2021; Katavouta and Williams, 2021; Roy et al., 2021; Menviel and Spence, 2024).

Here, we outline these links and then characterize the carbon and climate ocean processes that explain the large carbon and heat sinks and their feedback at global and regional SO scales (Figure 5.1).

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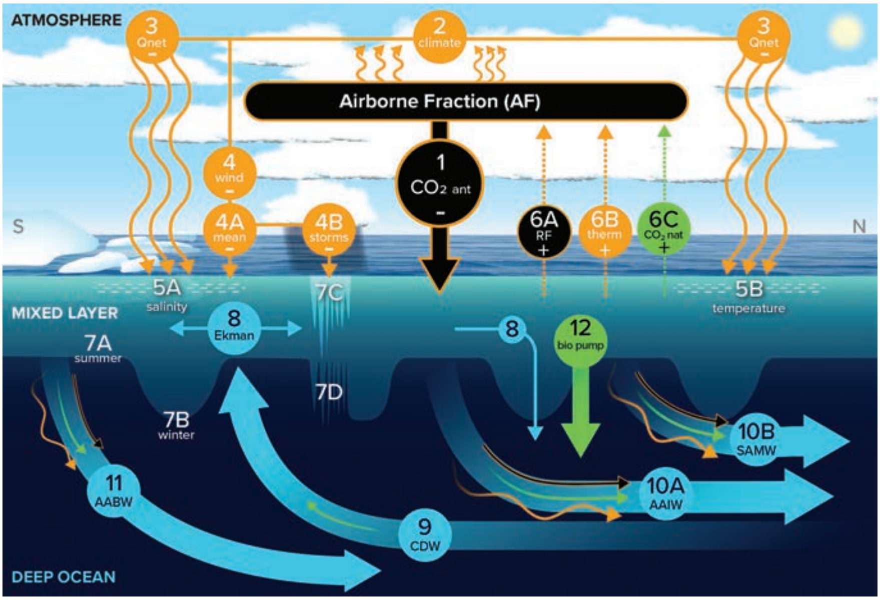

FIGURE 5.1 The key large-scale carbon–climate process fluxes that link the atmosphere–mixed layer–Meridional Overturning Circulation (MOC) systems in the Southern Ocean and drive the trends and variability of anthropogenic and natural CO_2 fluxes and the links with the Earth System. The SO feeds back to the ES mainly through the negative feedback of the anthropogenic CO_2 sink (1) on the airborne fraction (AF) of anthropogenic CO_2 in the atmosphere and the MOC in the ocean interior, with the mixed layer (ML) being the coupling domain. Antarctic Bottom Water (AABW); Circumpolar Deep Water (CDW); Antarctic Intermediate Water (AAIW); Sub-Antarctic Mode Water (SAMW).

The influence of the mean decadal (±0.75PgCy^{-1}) SO sink of CO_2 (1) on global climate arises from its contribution to maintaining the quasi-stable global atmospheric airborne fraction (AF) (±44%) of anthropogenic CO_2 (Canadell et al., 2023). The AF constrains the radiative forcing from exponentially increasing emissions of anthropogenic CO_2. This then drives the earth's energy imbalance that modifies climate (2) and its associated heat (3) and wind stress fluxes (4) (Figure 5.1). Emphasizing its role in a steady AF, the SO CO_2 sink is very sensitive to small changes in atmospheric CO_2 and is able to influence its variability (McKinley et al., 2020; Yun et al., 2022). The coupled nature of the carbon and heat negative feedback fluxes is further emphasized because they establish about 28% of the quasi-linear planetary relationship between warming and positive cumulative CO_2 emissions: the Transient Climate Response to cumulative carbon Emissions, a key metric for global carbon mitigation policy (Lamboll et al., 2023; Williams et al., 2023).

At a first-order level, the net heat fluxes (Q_{net}) (3) drive seasonal stratification and ML depth (MLD) through buoyancy changes driven by the seasonal cycle of

Q_{net} (5B), mainly north of the Polar Front (PF). South of the PF it does so through salinity fluxes (5A) linked to the seasonal sea-ice cycles (see Chapter 4). Overall, Q_{net} is the dominant driver of the seasonal cycle of the MLD, shallow in summer (7A) and deep in winter (7B) throughout all zones of the SO. Wind stress fluxes (4), linked to large-scale atmospheric circulation (see Chapter 3), can be divided into two main scales of forcing the physics of the ML: the mean annual westerly wind stress (4A) mainly drives advection associated with the large-scale Ekman transport (8) and the Antarctic Circumpolar Current (ACC). Together, they drive the SO part of the Meridional Overturning Circulation (MOC) (Bronselaer et al., 2018; Marshall & Speer 2012). Second, the synoptic storm scales (4B) drive the air-sea fluxes, mixing and MLD (7C), as well as the entrainment across the ML base (7D) (Monteiro et al., 2015; Nicholson et al., 2022; Carranza et al., 2024) (Figure 5.1).

The slower (10–100s years) global large-scale MOC is closed in the SO (8–11 in Figure 5.1). It is largely forced by the northward surface Ekman transport (8) induced by the mean westerly wind stress (4A) in the ACC and easterly wind stress south of the ACC (Rintoul, 2018). The Ekman flow (8) drives two responses that are critical to the carbon cycle: the upwelling of dissolved inorganic carbon (DIC)-rich (natural CO_2: green in Figure 5.1) Circumpolar Deep Water (CDW) to the base of the ML, and the subduction of ML water partially or wholly equilibrated with atmospheric CO_2 and heat in SAMW/AAIW north of the PF (Chen et al., 2022; Gray, 2024). South of the PF, the formation of AABW on the continental slopes of the Weddell and Ross seas is an important but smaller routing of anthropogenic CO_2 into the deep ocean interior (Rintoul, 2018; Hauck et al., 2023). Overall, the MOC brings natural CO_2 up to the surface and takes both natural and anthropogenic CO_2 into the ocean interior. It drives the storage of the anthropogenic CO_2 air-sea flux sink in the ocean interior in SAMW/AAIW (10A and 10B), and a significant proportion of the sink is in AABW (11) (Figure 5.1). It plays a critical role in understanding the role of SO feedback in glacial–interglacial transitions (Menviel and Spence, 2024) (see Section 5.2.2 and Chapter 4).

The MOC-linked natural carbon cycle is closed by the biological carbon pump (BCP) (12), an outgassing term (6C), and the subduction of a residual concentration in Mode and Bottom Waters (10A and 10B) (Hauck, Gregor et al., 2023). The MOC is also a small net emitter of natural CO_2, included in 6C, from both remineralized ocean production and river-borne flux of terrestrial carbon (Hauck et al., 2023). Seasonal and synoptic fluxes of CDW across the ML base not only transport natural CO_2 but also nutrients (Nitrogen, Silicate, and Iron), which together with the light profile set by the seasonal MLD, are critical to regulate and ultimately limit net primary production (NPP) (Boyd et al., 2024). NPP drives the BCP (12), which significantly offsets and reduces the magnitude of the outgassing of natural CO_2 (6C) and transports carbon into the ocean interior (12) (Thomalla et al., 2023) (see Sections 5.3.1 and 5.3.2).

The interaction of carbon-concentration and carbon–climate feedback from the atmosphere and the ocean interior in the ML of the SO lead to three potentially important positive feedback fluxes (6A–6C). These feedback fluxes are the weakening of the carbonate buffer or Revelle Factor (RF) (6A), the influence of warming on the temperature-dependent solubility of CO_2 (6B), and the mean wind-dependent (4A) outgassing flux of natural CO_2 (6C) upwelled in CDW (9). These could, under sustained high positive emissions, measurably weaken the main SO negative feedback (1), and hence weaken its mitigating impact through the AF (Figure 5.1). Each of these feedback fluxes has been observed to strengthen during the contemporary period, making observable changes to the magnitudes and variability of CO_2 in the ML but not enough, singly or collectively, to impact the trend in the AF (Landschützer et al., 2018; Canadell et al., 2023).

In the following sections, we focus on the characteristics and processes that drive the links and feedback in the SO. We start with the mean constraints and variability of the large-scale anthropogenic CO_2 negative feedback in the contemporary period (Section 5.2.1), the possible drivers of paleo trends and variability with a focus on the transition out of the Last Glacial Maximum (LGM; Section 5.2.2), and the emergent positive feedback fluxes under projected high and low emission scenarios (Section 5.2.3). In the last section, we examine the main physical and biogeochemical processes in the ML that link the atmosphere to the deep ocean, and hence the SO to the ES (Sections 5.3.1 and 5.3.2). In each section, where appropriate, we highlight ongoing and future research gaps.

5.2 The SO Carbon Cycle: Present, Past, and Future

5.2.1 The Contemporary Constraints: Mean State, Trends, and Variability

The carbon cycle in the SO comprises several constituent fluxes. The anthropo genic CO_2 fluxes (F_{ant}) (1) are mainly mediated by physical processes (momentum and thermal) (3,4 and 6A,6B), the natural or preindustrial fluxes (F_{nat}) (9–11), mediated by ML physics and biogeochemical processes, and the river fluxes (F_{riv}) (included in 6C), which balance a part of land-derived carbon fluxes into the ocean (Figure 5.1) (Hauck et al., 2020).

5.2.1.1 Decadal Mean State

The past decade has seen significant advances in the constraints and drivers of the decadal mean, trends, and variability of air-sea CO_2 fluxes as part of the negative feedback driven by anthropogenic CO_2 in the SO (Figure 5.2) (Hauck et al., 2023; Gray, 2024). CO_2 fluxes from forced models (global ocean biogeochemistry models, GOBMs) and observation-based reconstructions (surface ocean pCO_2-based data products, pCO_2-products) and observation-based ocean interior estimates of carbon inventory provided independent constraints for air-sea fluxes (Figure 5.3) (Gruber et al., 2019).

The most recent assessment of this mean multi-decadal budget shows a good agreement between air-sea CO_2 fluxes from observation-based reconstructions ($-0.73\pm0.07 PgCy^{-1}$) and forced biogeochemical models ($-0.75\pm0.28 PgCy^{-1}$)

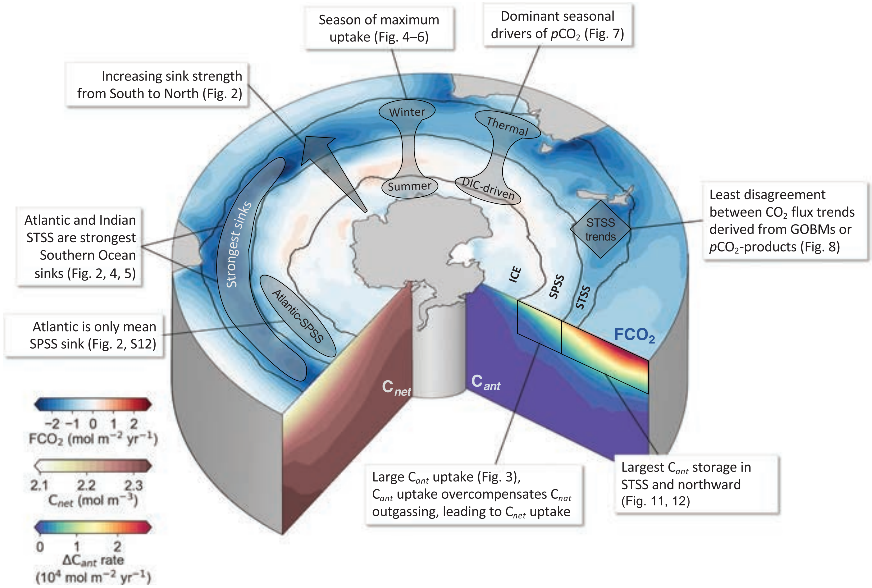

FIGURE 5.2 Main characteristics of the Southern Ocean carbon cycle 1985–2018. The surface ocean colour shading depicts the net air-sea CO2 flux (FCO_2) as the ensemble mean average from pCO_2-products and global ocean biogeochemistry models (GOBMs). Blue denotes a CO_2 flux into the ocean, and red a flux out of the ocean. The section on the right shows the zonally integrated anthropogenic carbon (C_{ant}) accumulation rate in the ocean interior from GOBMs. The section on the left shows the zonally averaged concentration of total (or "net") carbon (C_{net}). Ice-covered biome (ICE), Subpolar Seasonally Stratified Biome (SPSS), and Subtropical Seasonally Stratified Biome (STSS) (Hauck et al., 2023).

for the period 1985–2018, acknowledging the partial seasonal and regional compensation of biases (Hauck et al., 2023). Moreover, there is a strong correlation between annual air-sea fluxes and storage changes (r^2=0.78), but the slope points to a storage change that is 60% of the air-sea flux (Figure 5.3), with the remainder exported to thermocline waters outside the SO (Hauck et al., 2023).

5.2.1.2 The Spatial Character of the SO CO_2 Fluxes and Storage

Strong meridional gradients characterize SO carbon fluxes: the subtropical seasonally-stratified biome (STSS) at the northern edge of the SO is quantitatively one of the most important regions for ocean carbon uptake globally (see Figure 5.2) (Hauck et al., 2023). The STSS was already an uptake region in pre-industrial times, i.e., for natural CO_2 due to winter cooling, high wind speeds, and deep mixing leading to subduction and associated transport of carbon away from

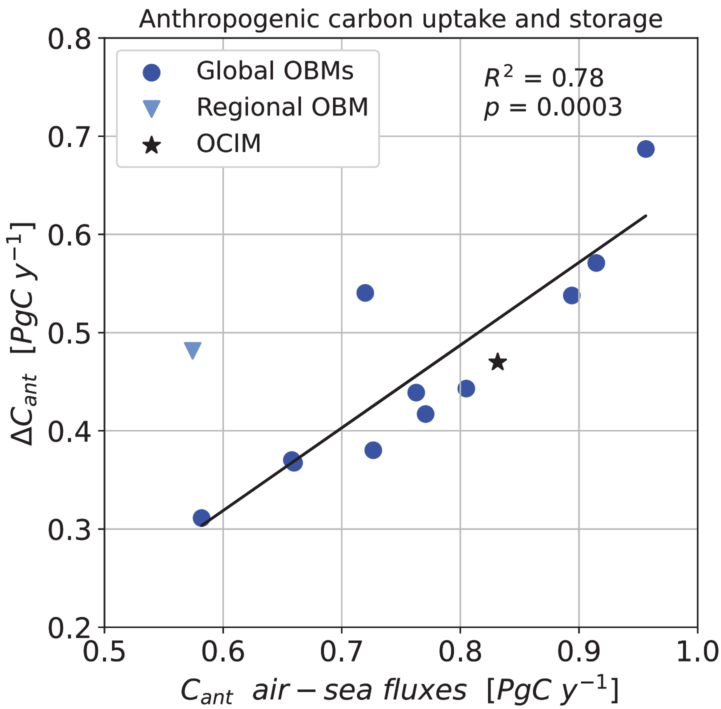

FIGURE 5.3 Shows the quasi-linear ($r^2 = 0.78$) relationship between the air-sea and interior storage fluxes of the Southern Ocean. It depicts both fluxes calculated from global and regional ocean biogeochemical models (OBMs) and observations assimilation based inverse models (OCIMs). Redrawn from Fig. 13b in Hauck et al. (2023).

the surface and into the ocean interior (Takahashi et al., 2009) (see also Chapter 4). Rising anthropogenic carbon concentrations in the atmosphere amplify the carbon flux into the ocean in the STSS. Upwelling of old and, thus, naturally carbon-rich deep waters characterizes the subpolar seasonally stratified (SPSS) and partially ice-covered (ICE) biomes further south. The carbon exposed to surface processes was primarily lost to the atmosphere in preindustrial times (Hoppema, 2004). Human CO_2 emissions lead to a more significant CO_2 concentration in the atmosphere than in the surface ocean. Thus, anthropogenic carbon uptake in SPSS and ICE biomes suppresses natural CO_2 outgassing (Hauck et al., 2023).

5.2.1.3 Surface Fluxes vs Carbon Storage in SO Interior

In this section, we focus on explaining the links between water masses, carbon release into the atmosphere, and carbon storage in the ocean interior. The underlying physical processes are covered in Section 5.3.1 below and Chapter 4. Discrete observations of interior ocean biogeochemical variables from research vessels allow us to estimate anthropogenic carbon accumulation in the ocean interior with several assumptions (Gruber et al., 2019). These estimates provide an independent constraint on the surface air-sea CO_2 fluxes. In addition, an ocean inverse (abiotic) model assimilating tracers of circulation, such as CFCs, provides another quasi-independent constraint (DeVries et al., 2019).

The general pattern of anthropogenic carbon (C_{ant}) accumulation in the ocean interior is robust, mainly influenced by water mass formation and transport. The uptake of anthropogenic carbon in surface waters (1), its northward Ekman-transport (8), and eventual subduction, mainly in winter, as Mode and Intermediate waters (10A-B) explain the growing inventory of anthropogenic CO_2 in ocean interior (Langlais et al., 2017; Rintoul, 2018; Gruber et al., 2019; Sallée et al., 2023). This process leads to the characteristic accumulation of the $C_{\mathbf{ant}}$ inventory in the subtropical ocean interior north of the mid-latitude peak in surface fluxes (Hauck et al., 2023). A smaller and rather poorly quantified and climate-sensitive portion of surface waters travels polewards towards the Antarctic continent, where Antarctic Bottom Water formation (11) leads to carbon sequestration in the deep to the bottom ocean for time-scales of centuries and longer (Zhou et al., 2023).

Although uncertainties in carbon inventory changes are also substantial, those estimates suggest that a majority of models underestimate SO anthropogenic carbon uptake and accumulation by ~10–20% (Hauck et al., 2023), in line with global assessments based on oxygen-to-nitrogen ratios and atmospheric inversions (Friedlingstein et al., 2023). This uncertainty exists despite the good representation of the thermal drivers from atmospheric forcing reanalysis products. This uncertainty points to the role of ventilation as the bottleneck for ocean uptake of anthropogenic carbon. Its complexity involves many physical processes in the MOC and MLD dynamics (Chapter 4), and the current generation of ocean models does not adequately represent them.

5.2.1.4 Decadal and Interannual Trends and Variability

The coherence in the multi-decadal trends and interannual variability of the air-sea fluxes of anthropogenic CO_2 in the SO and the global ocean point to a significant influence of SO processes in the global ocean negative feedback of anthropogenic CO_2 (Canadell et al., 2023; Hauck et al., 2023). The three main characteristics of the SO carbon sink on these time scales are its slowdown in the 1990s, its subsequent reinvigoration (2001–2018), and the divergent slopes of the ocean sink between GOBMs and pCO_2-products, with the latter suggesting a faster growth both in the SO and global ocean (Hauck et al., 2020; Friedlingstein et al., 2023; Hauck et al., 2023).

The main hypotheses seeking to explain the differences between the "slowdown" and "reinvigoration" link them to ES carbon–climate feedback fluxes:

- Strengthening of the Southern Hemisphere westerly wind belt associated with the Southern Annular Mode results in enhanced upwelling of carbon-rich deep water (Le Quéré et al., 2007; Gregor et al., 2018; Mayot et al., 2023). This strengthening could explain the slowdown in the SO carbon sink in the 1990s, but much less convincingly, the reinvigoration in 2001–2018.

- A global signal from the Mt Pinatubo volcanic eruption and associated surface cooling, together with the slower atmospheric CO_2 growth rate in the 1990s, led to slower global growth of the ocean carbon sink in the 1990s and a recovery in the 2000s. This decadal signal is particularly evident in the SO (Gregor et al., 2019; Hauck et al., 2020).
- There was an increased upper-ocean overturning circulation in the 1990s (DeVries, Holzer and Primeau, 2017), which is in qualitative agreement with the argument of strengthening westerly winds. The reported reversal of this trend in the 2000s explains the reinvigoration of the ocean carbon sink. However, this study did not address the drivers of the weakened upper-ocean overturning circulation.

The diverging trends of GOBMs and pCO_2-products are an area of active research. Recent results suggest that the currently available observations and their distribution may not be sufficient to allow the current generation of pCO_2-product methodologies to constrain the trends, especially in the data-poor SO (Gloege et al., 2021; Hauck et al., 2023). At the same time, the effect of potential biases in ocean biogeochemistry models on the trend must be examined (e.g., the underestimation of anthropogenic carbon inventories and their drivers).

5.2.1.5 Seasonal Cycle and Intraseasonal Variability

The canonical SO seasonal cycle of pCO_2 has elevated magnitudes in winter and strong sinks in summer (Takahashi et al., 2009). However, both seasonal and intra-seasonal cycles of ΔpCO_2 (the difference between partial pressure of CO_2 in the ocean and atmosphere) and the fluxes of CO_2 are the strongest modes of variability in the SO (Gregor, Kok and Monteiro, 2018). Thus, when observed and modelled at high spatio-temporal resolution, the seasonality of pCO_2 is characterized by a mosaic of seasonal and intraseasonal modes of variability (Figure 5.4) linked to the interaction of seasonal stratification (5A and 5B in Figure 5.1) and synoptic storm forcing (7C and 7D in Figure 5.1) (Djeutchouang et al., 2022).

Broadly, intraseasonal modes predominate in the high mesoscale eddy zones north of the PF and the seasonal cycle to the south of the PF (Figure 5.4). Next to ML effects of seasonal stratification (Swart et al., 2023) (Chapter 4), a further critical influence in the seasonality of pCO_2 is the response of pCO_2 to seasonal and intraseasonal thermodynamic (thermal) and biogeochemical and circulation (non-thermal) drivers of pCO_2 and FCO_2 (Nicholson et al., 2022; Toolsee et al., 2024). These two drivers of pCO2 variability in the ML typically oppose each other, and their balance can be biased one way or the other in ESMs (Mongwe et al., 2018).

Even with the recent advances, the role of the seasonal drivers of pCO_2 in the interannual variability and trends in the CO_2 fluxes remains a subject of ongoing

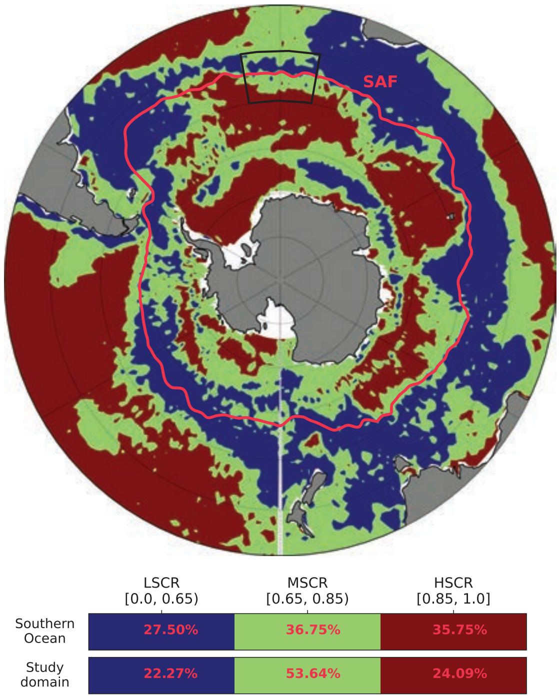

FIGURE 5.4 The mosaic of seasonal and intraseasonal modes of variability that characterize the anthropogenic air-sea CO_2 net-fluxes in the Southern Ocean. It depicts the seasonal cycle reproducibility (SCR) as a metric to quantitatively characterize the seasonality of the fluxes from a mesoscale resolving model. SCR quantifies the correlation between the interannual seasonal cycle and the mean decadal seasonal cycle. The SCR has three categories: high SCR (brown) are areas characterized by the seasonal cycle; low SCR areas (blue) depict synoptic intraseasonal variability; medium SCR areas (green) are a hybrid between the two extremes. Importantly, it highlights that the communication between the atmosphere and the MOC, which drives the SO-ES links, is modulated by the synoptic-seasonal process modes for both CO_2 and heat fluxes in the ML (see Djeutchouang et al. (2022) for the calculation of SCR).

research (Djeutchouang et al., 2022; Rodgers et al., 2023). An increasing diversity of autonomous platforms is gradually addressing the spatial and temporal sparseness of seasonal CO_2 observations in the SO (Monteiro et al., 2015; Bushinsky et al., 2019; Sutton et al., 2021). Moreover, Observing System Simulation Experiments (OSSEs) point to the sensitivity of uncertainties and biases of CO_2 flux reconstructions on the extent to which observations match the critical scales of variability of the processes (Djeutchouang et al., 2022; Hauck et al., 2023).

5.2.1.6 Emerging Contemporary Carbonate Positive Feedback: Ocean Acidification

The ocean uptake of anthropogenic CO_2 shifts carbonate equilibria towards dissolved CO_2 (the only form that can exchange with the atmosphere), and thus reduces the carbonate system's buffer capacity (6A) and hence the amount of additional carbon that can be taken up (Egleston et al., 2010). The preindustrial SO had the lowest mean buffering capacity in the open ocean because of the upwelling and entrainment of high concentrations of C_{nat} from upwelled CDW (Sabine et al., 2004; Chen et al., 2022). This low buffering capacity makes it one of the areas of the ocean where the carbonate system and hence both the CO_2 sink and ocean acidification are most sensitive to increasing emissions of anthropogenic CO_2 (Matear and Lenton, 2008). This positive feedback process is why the ocean, particularly the SO under high positive emissions, will take up a decreasing percentage of those emissions (Canadell et al., 2023).

The lower buffering capacity also leads to a stronger seasonal cycle of pCO_2 and CO_2 flux, as any seasonal variation in one of the drivers of pCO_2 (DIC, T) amplifies pCO_2 change (Hauck and Völker, 2015; Landschützer et al., 2018). This process is expected to further amplify the seasonal cycle in the future SO with its extreme seasonal changes in thermal, wind, and biological drivers and has been shown to strengthen the carbon sink driven by the biological carbon pump (Hauck and Völker, 2015; Mongwe et al., 2024). The quantitative contribution of this seasonal effect is hard to isolate. However, Fassbender et al. (2022) suggest that globally, the seasonal cycle negative feedback increases ocean CO_2 uptake by 8%, thus only partially counteracting the mean state positive buffer factor feedback that reduces carbon uptake by 60%. Strengthening the carbonate positive feedback through pH and acidification may also be a factor in the recently proposed strengthening of iron stress-driven weakening of primary production and potentially to the BCP (Ryan-Keogh et al., 2023). Although mechanisms are changing, the positive feedback fluxes are not yet large enough to impact the AF of anthropogenic CO_2 (Canadell et al., 2023).

5.2.2 The Past: Last Glacial–Inter-Glacial Transition

5.2.2.1 Physics vs Biogeochemical Drivers of the CO_2 Sink

During the last glacial–interglacial transition (i.e., the last deglaciation, ~21–29 thousand years ago), a relatively rapid release of CO_2 from the SO contributed to the deglacial warming of the planet. This carbon–climate feedback provides strong evidence for the coupled nature of the planetary climate and the SO physics and biogeochemical processes. It is a potential paleo analogue for the magnitude and direction of modern feedback. The concentration of atmospheric CO_2 increased by 90 ppm during the last deglaciation in several centennial-scale steps of about 12 ppm (Marcott et al., 2014). While these deglacial atmospheric CO_2 jumps, of ~0.04 ppm yr^{-1}, probably present the highest natural rate of atmospheric CO_2

increase, they are still much lower than contemporary rates of anthropogenic CO_2 increase (~1ppm yr^{-1} for 1900–2019) (Canadell et al., 2023). It has been suggested that some of these abrupt phases of atmospheric CO_2 increase were in part due to enhanced CO_2 outgassing from the SO that could result from a weaker biological pump due to reduced dust input, reduced SO sea-ice cover, reduced SO stratification, and enhanced SO upwelling from changes in the strength and position of the Southern Hemispheric (SH) westerlies.

5.2.2.2 Physical Carbon–Climate Feedback Fluxes

SO sea-ice cover was most likely twice as large at the LGM than during pre-industrial (e.g., Green et al., 2022). As sea-ice modulates the air-sea exchange of CO_2 and buoyancy at the surface of the SO, the deglacial sea-ice retreat could lead to a significant increase in atmospheric CO_2 (Marzocchi and Jansen, 2019). The direct, air-sea gas exchange impact of changes in sea-ice extent on atmospheric CO_2 is probably small, 3 ppm at most (Gottschalk et al., 2020). However, a more extensive SO sea-ice cover could indirectly lead to an increase in deep carbon content, by increasing the vertical density gradient in the SO and leading to a shoaling of the interface between the abyssal and deep overturning cells in the SO (Marzocchi and Jansen, 2019). The deglacial sea-ice retreat would thus reduce stratification and increase mixing, increasing atmospheric CO_2. However, such a mechanism has yet to be demonstrated with ES models, in part because it still needs to be reconciled with the fact that numerical experiments simulate a decrease in deep ocean carbon content and an increase in atmospheric CO_2 as the Antarctic Bottom Water transport intensifies (e.g., Menviel et al., 2014).

An increase in SO upwelling due to a strengthening or poleward shift of SH westerly winds could have contributed to the deglacial atmospheric CO_2 increase. Paleo-proxy records have provided evidence for enhanced SO upwelling at the beginning of the deglaciation (Anderson et al., 2009) and a deglacial poleward shift of SH westerlies (Gray et al., 2023). Modelling studies also show that a strengthening or poleward shift of the SH westerlies enhances SO upwelling of carbon-rich deep waters, thus leading to CO_2 outgassing in the SO (e.g., (Gottschalk et al., 2020). However, while coupled climate models consistently display a poleward strengthening of the SH westerlies over the coming century, no consistent picture yet emerges for the LGM (e.g., Chavaillaz, Codron and Kageyama, 2013).

5.2.2.3 Biogeochemical Carbon–Climate Feedback

Due to the globally colder, drier conditions and associated changes in vegetation cover during glacial times, dust deposition at high southern latitudes was at least twice as high during the LGM ~21,000 years ago) than in pre-industrial (Lambert et al., 2012), resulting in a higher aeolian iron input into the SO (e.g., Martínez-Garcia et al., 2011). As iron is a limiting nutrient in the SO, enhanced

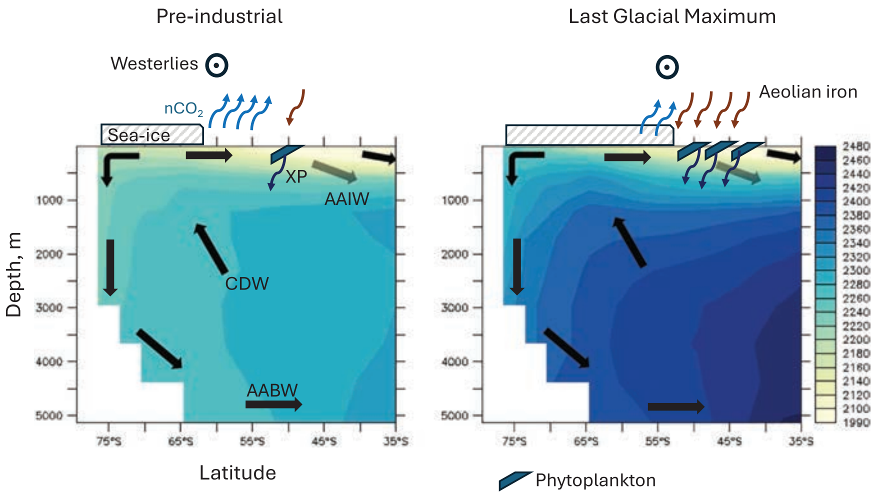

FIGURE 5.5 Glacial vs deglacial states and fluxes: State of the Southern Ocean at the Last Glacial Maximum (LGM, right) compared to the pre-industrial period (left) as simulated with an ES model of intermediate complexity (Menviel et al., 2017). Zonally averaged DIC concentration (shaded, µmol/L) showing a much higher DIC concentration in the deep ocean at the LGM resulting from enhanced stratification and higher export production due to enhanced aeolian iron input. The processes leading to enhanced stratification include a more extensive sea-ice cover, saltier AABW, a shoaling of NADW, and potential changes (weakening, equatorward shift) of SH westerlies, reducing the upwelling of DIC-rich deep waters to the surface of SO.

iron input could enhance export production in the sub-Antarctic zone during glacial times (Martin, 1990). On the contrary, the decrease in aeolian iron in the SO during the last deglaciation could have led to an atmospheric CO_2 increase of ~12 ppm (Saini et al., 2022). However, as the dust flux decreases ~2000 years before the CO_2 increase during the last deglaciation, the impact of reduced iron fertilization on the deglacial atmospheric CO_2 increase is questionable (Lambert et al., 2012).

A deglacial decrease in SO stratification, either through changes in buoyancy or dynamic (stronger/poleward shifted westerlies) forcing, would have lowered deep ocean carbon storage, thus increasing atmospheric CO_2 (Skinner et al., 2010;). However, explaining and simulating enhanced SO stratification remains challenging during glacial times. Progress still needs to be made in our understanding of the SO's role in driving past changes in atmospheric CO_2.

5.2.3 *Future: Century-Scale Projected Feedback*

During the contemporary period, the SO has contributed consistently to the quasi-linear strengthening of the global ocean anthropogenic CO_2 sink under exponential CO_2 emissions over the past six decades (Canadell et al., 2023; Hauck et al., 2023). However, future decadal to multi-century projections of trends and both temporal and spatial variability of this negative ES CO_2 feedback is that they are strongly emission scenario-dependent (Chikamoto and DiNezio, 2021; Ridge and McKinley, 2021). Thus, the sensitivity of emergent positive feedback in the SO to global emission scenarios is critical to projecting complex responses to the trends and variability of the CO_2 sink. Critically, while the efficiency of the CO_2 sink has been steady over the past 5 decades, it is projected to decrease under both positive and negative emission scenarios towards the end of the century but driven by different feedback fluxes (Ridge and McKinley, 2021).

The three main drivers of carbon-concentration and carbon–climate positive feedback fluxes are (a) weakening of the buffering capacity of the carbonate system, the strongest feedback, driven by the sustained exponentially increasing emissions, (b) reduced solubility of CO_2 from the scenario-dependent warming of the ML and ocean interior; and (c) long-term trends and decadal variability in the SO part of the MOC linked to the mean westerly and easterly wind stress as well as storm intensities (Gentile et al., 2023). The domain common to these three drivers is the surface ML, which highlights the complex role of the ML in projecting carbon and climate feedback. It also highlights a recognized weakness in ES projection models because models do not adequately resolve the scales at which these drivers interact in the ML (Hewitt et al., 2022; Swart et al., 2023). This a current research topic.

The carbon-concentration (β) and carbon–climate (γ) feedback parameters provide a quantitative estimate of the sensitivity of the carbon cycle to anthropogenic forcing (Katavouta and Williams, 2021). The feedback parameters were calculated from SO fluxes and storage rates from idealized 1% positive emission model scenarios were used to derive these feedback parameters. These analyses confirm that the carbon-concentration feedback dominates the projected response of the CO_2 sink. In contrast, the carbon–climate feedback is relatively weak because the increased carbon storage from the BCP, linked to a slower MOC, is offset by the warming-linked positive feedback (Katavouta and Williams, 2021).

Century-scale ESM projections under high-CO_2 positive emissions (SSP5 – 8.5) show a sustained strengthening of the SO CO_2 sink until the last two decades of the 21st century, primarily driven by the exponential increase in emissions on the air-sea gradient of pCO_2 (Chikamoto and DiNezio, 2021). The positive feedback from weakening the carbonate buffering capacity in the ML drives the subsequent weakening of the CO_2 sink in the 22nd century. After saturation, it leads to the relative strengthening of the impact of thermal and alkalinity drivers on pCO_2 from carbon–climate feedback on solubility, stratification, sea-ice, and MOC changes (Chikamoto and DiNezio, 2021; Ridge and McKinley, 2021). Negative emissions are projected to weaken the SO CO_2 sink in response to the decreasing atmospheric pCO_2 combined with the "back-pressure" created by the weak buffering capacity forced by the positive emissions (Zickfeld et al., 2016; Ridge and McKinley, 2021).

While the projected response of the SO BCP under strong emission scenarios remains uncertain (Henson et al., 2022), its potential impact on the anthropogenic CO_2 sink may yet become significant because of its impact in amplifying the seasonal cycle of pCO_2 under reduced buffering capacity (Figure 2 in (Hauck and Völker, 2015; Fassbender et al., 2022) for global scale. In the SO, this amplification effect could enhance CO_2 storage, offsetting some of the impacts of the positive feedback (Hauck and Völker, 2015). Beyond the potential amplification effect, this interaction has a potential impact on the geographical location of the dominant CO_2 sink. Mongwe et al. (2024) showed that at the end of the century in scenario SSP5 – 8.5, the strengthening of the thermally driven positive feedback on CO_2 solubility north of the PF linked to the amplification of the pCO_2 seasonal cycle south of the PF drives a regime shift in the location of the main anthropogenic CO2 sink from the sub-Antarctic zone to the sub-Polar zone.

5.3 ML Physical and Biogeochemical Processes Influencing Carbon Feedback Fluxes

There are two critical interfaces in considering the physical processes linked to the variability, trends, and feedback fluxes of anthropogenic CO_2 fluxes: (1) the air-sea interface, which connects the lower marine atmospheric boundary layer to the surface ocean, and (2) the ML base, which connects the surface ocean ML to the ocean interior and hence the MOC. Figure 5.6 presents some of the critical processes involved in the CO_2 pathways from the atmosphere to the deep ocean, which drive the complex spatial structure of seasonal to intraseasonal modes of variability of FCO_2 fluxes (Figure 5.4). Hauck and Völker (2015) and Sallée et al. (2023) showed systematic errors derived from model estimates of the MLD in the SO, which they argue is associated with an incomplete description of the turbulent processes in the ML. These MLD biases have several knock-on effects in modelling, such as sea surface temperature warming by several degrees in the SO. Sallée et al. (2023) identify ventilation, i.e., the rate at which atmospheric CO_2 reaches the deep ocean and vice versa, as the critical process for inhibiting predictions on decadal timescales (Chapter 4).

5.3.1 The ML and Its Two Boundaries: Carbon–Climate Feedback Bridge

Turbulence plays a crucial role in driving CO_2 transfer and is the process primarily responsible for CO_2 and heat crossing both boundaries. In addition, the processes that drive the exchanges of CO_2 across the ML boundaries involve mechanisms that include lateral stirring, advection, and turbulent diffusion derived from wind, waves, and buoyancy (Swart et al., 2023).

5.3.1.1 Sea Ice and Buoyancy Forcing South of the PF

An exception to the processes described above is the sea-ice-impacted SO, where enhanced buoyancy forcing from sea-ice melt (freshwater flux) maintains stable shallow MLs, limiting exchanges between the surface and subsurface (Giddy et al., 2021). Beneath the surface, ocean ML are regionally varying reservoirs of carbon and heat connected to the variations of upwelling and subduction linked to the MOC and with flow interactions with topography. The upwelled MOC establishes the boundary conditions at the base of the ML as an essential component in explaining the spatial and temporal distribution of SO FCO_2.

5.3.1.2 The Role of Storms

The strong winds from regular storms excite wakes of shear-driven turbulent dissipation (Figures 5.1 and 5.6), which explains a significant amount of ML mixing on daily time scales in different regions of the SO. The passage of strong storms drives deep-mixing that can access and entrain unventilated subsurface carbon into the surface ML, reversing the gradient of ΔpCO_2 (i.e., the difference in air-sea partial pressures of CO_2), resulting in significant outgassing events of CO_2 to the atmosphere (Nicholson et al., 2022). However, when this deep water entrains into the ML, it may also supply surface waters with limiting

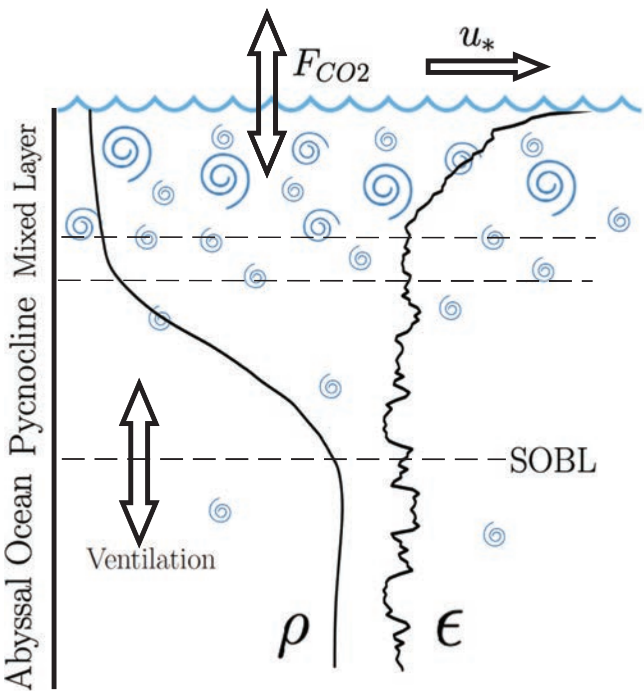

FIGURE 5.6 Overview of the processes at the surface ocean and the base of the ML, which are the two boundaries for CO_2 entry and exit to/from the mixed layer. It depicts typical profiles of ocean density (ρ) and dissipation (ε) with corresponding estimates of the mixed layer depth based on these parameters.

micronutrients in support of enhanced production (Nicholson et al., 2019; Ryan-Keogh and Thomalla, 2020) and potential carbon drawdown that can offset CO_2 outgassing. The cumulative biogeochemical outcome of storms thus depends on the CO_2:iron ratio in entrained waters (Boyd et al., 2024). Storms also drive diffusive heat transfer beneath the ML (notably in the Sea Ice Zone (SIZ) in summer), accelerating warming and erosion of the subsurface winter water layer, a critical barrier between the atmosphere and carbon-rich CDW in this region (Giddy et al., 2023).

5.3.1.3 Role of Small-Scale Dynamics in Large-Scale Feedback

Of crucial importance for rapid exchanges of properties across the surface ocean ML are 'fine-scale' dynamics, which are prevalent across the SO (Figure 5.1 in (Hewitt et al., 2022; Swart et al., 2023). However, substantial uncertainty persists with regards to the role of fine-scale processes in SO uptake of CO_2, its redistribution, and storage, and as such, there remains much debate regarding the spatio-temporal scales of motion required to be explicitly resolved by ES models (Hewitt et al., 2022). High-resolution process modelling studies have provided some insights and show that fine-scale dynamics play an essential dynamical role in establishing a "bridge" between the atmosphere and the oceanic interior (Rosso et al., 2017; Balwada et al., 2018). Since the development of autonomous observing systems (e.g., ocean gliders, floats, and seal tags) and high-resolution satellite imagery, observing and understanding the role of fine-scale dynamics in driving rapid changes to the mixed-layer and its properties has advanced significantly (Sallée et al., 2023; Swart et al., 2023; Thomalla et al., 2023). A handful of process studies observe the impact of mesoscale eddies on FCO_2 (e.g., Smith et al., 2023). However, these examples show contrasting responses of FCO_2 in anticyclonic eddies (e.g., driving both uptake and outgassing), highlighting the need for more observational constraints of these processes.

5.3.2 Biogeochemical Processes Influencing Carbon Feedback Fluxes in the SO

Biological and physical processes (e.g., photosynthesis, remineralization, sinking, and subduction) drive the BCP that generates, transports, and stores enough carbon in the oceans' interior (years to centuries) to offset natural CO_2 outgassing from upwelled pre-industrial DIC. The SO BCP significantly contributes to the natural CO_2 sink, removing ~3 Pg of carbon from surface waters annually (i.e., 33% of the global flux). In addition, the SO BCP regulates nutrient supply to low-latitude thermocline waters in support of NPP and associated carbon export (Sigman and Boyle, 2000; Sarmiento et al., 2004). As such, any perturbations to the SO BCP may drive important global climate feedback (Huang, Fassbender and Bushinsky, 2023).

The magnitude and functioning of the BCP are sensitive to a wide range of processes that impact both the epipelagic and mesopelagic, and hence, projecting the response of the BCP to the cumulative effect of many climatic feedback fluxes is problematic (Figure 5.7) (Henson et al., 2023).

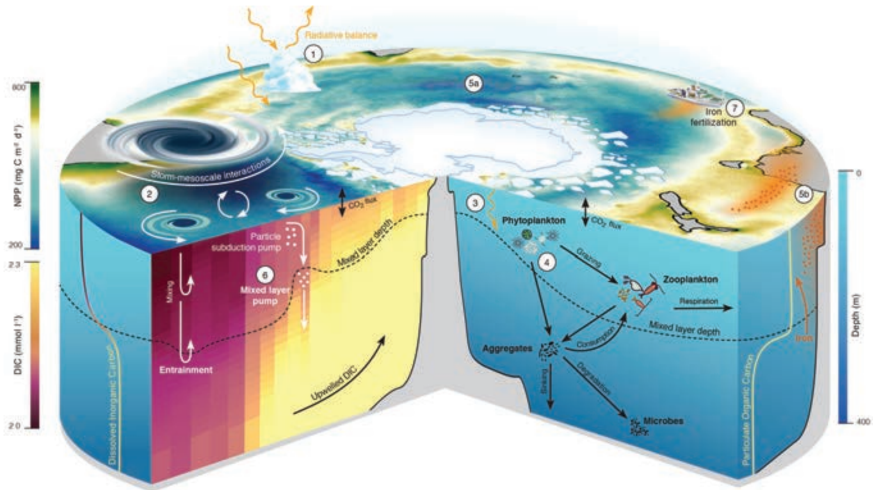

FIGURE 5.7 Biogeochemical feedback processes: the surface map of the climatology (1998–2023) of Southern Ocean net primary production (NPP – mg C m^{-2} d^{-1}) generated with the CAFÉ model (Silsbe et al., 2016) highlights the patchy distribution of NPP associated with frontal features, topography, and sea ice. The profile (far left) and section map (left) depict the change in the distribution of dissolved inorganic carbon (DIC – mM) with depth and latitude. The profile of particulate organic carbon (far right) depicts a distribution that is high at the surface and decreases exponentially below the mixed layer. The numbers reflect different biogeochemical feedback processes: (1) Changes in phytoplankton community composition impact atmospheric particle nucleation, cloud formation, and regional radiative forcing. (2) Storm interactions with fine-scale ocean dynamics determine mixed layer characteristics that impact nutrient and light supply in support of NPP. (3) Changes in sea ice alter nutrient and light availability, which impacts NPP and the ocean carbon cycle. (4) Changes in phytoplankton community composition in response to climate forcing (e.g., warming and ocean acidification) impact the efficiency of carbon export and storage. (5a) Low NPP in iron-limited waters is contrasted to the more productive waters associated with dust deposition and upwelling at continental margins, (5b) highlighting how any climate-induced change to iron supply, availability, or demand may impact trends in NPP and the BCP. (6) Climate-driven changes in mixed layer dynamics and the eddy field will impact carbon export via the particle injection pumps. (7) Interventions to stimulate the ocean's BCP, such as purposeful ocean iron fertilization, are proposed as ocean carbon dioxide removal (CDR) strategies; however, their efficacy is actively contested.

5.3.2.1 Cloud Formation: the Role of Floristics in Atmospheric Particle Nucleation

SO cloud, aerosol, and precipitation processes are fundamentally different, poorly understood, and simplistically represented in atmospheric models, resulting in substantial surface radiation and SST biases in ESMs (Mace, Protat and Benson, 2021). Aerosols are integral to cloud formation and life cycles and directly influence the radiation budget. Although rarely observed, measurements suggest that unique chemistry drives the nucleation of cloud droplets over Antarctica and the SO (Jokinen et al., 2018). Given the scarcity of nucleating agents, marine biogeochemical processes may contribute disproportionately to modulating cloud properties through the production of key groups of sulphur, oxidized nitrogen, halogenated and oxygenated Volatile Organic Compounds (Sellegri et al., 2021). However, these molecules and their provenance are complex, poorly understood, and rarely observed (Sellegri et al., 2021). Climate-change-mediated changes in phytoplankton community structure may feedback on the production of these precursor compounds triggered, for example, by altered rates of formation of volatile nitrogen and sulphur compounds, impacting cloud formation and their consequent effects on regional radiative forcing.

5.3.2.2 Sea-Ice Retreat and Its Influence on MIZ and Under-Ice Blooms

In 2023, the annual mean coverage of sea-ice reduced to 9.81 million km^2, followed by a sustained trend of increasing sea-ice extent in East Antarctica (Hobbs et al., 2024; Roach and Meier, 2024), which is indicative of a phase shift (Purich and Doddridge, 2023) with additional evidence of retarded equatorward sea-ice advance. The increased sea-ice retreat of 1 million km^2 changes ocean physics (buoyancy flux), optics (underwater irradiances), and chemistry (iron supply/dissolved organic carbon release), resulting in multi-faceted feedback fluxes that alter carbon cycling by changing patterns in NPP and summertime CO_2 drawdown. There is also emerging evidence of the importance of under-ice and Marginal Ice Zone (MIZ) blooms. How do these blooms contribute to NPP? What is the fate of these CO_2-undersaturated waters as the sea-ice advances in wintertime? Hauck et al. (2023) reported that two major unknowns on the carbon cycle were the role of summer biology and winter physics. The extreme sea-ice retreat, along with its retarded advance, adds further uncertainties to these unknowns.

5.3.2.3 Phytoplankton Community Structure

Phytoplankton responses to anthropogenic forcing are a key feedback on climate since cell size and elemental stoichiometry impose fundamental constraints on growth rates, community structure, and carbon biogeochemistry (Finkel et al., 2010). For example, two key species, coccolithophores, and diatoms, drive distinctive carbon cycle components and occupy different biogeographical regimes.

Coccolithophores often dominate at mid-latitudes (Balch et al., 2016), where calcification and the downward flux of $CaCO_3$ help regulate the carbon pump. Ocean warming and southward migration of the ACC fronts may drive a poleward expansion of large subantarctic coccolithophores (Winter et al., 2014), enhancing export. However, acidification may counteract these changes. Reduced pH will also impact $CaCO_3$ ballast, decreasing coccolithophore sinking rates and reducing ocean storage (Barker, Higgins and Elderfield, 2003). Diatoms are efficient exporters of carbon and often dominate in polar waters (Tréguer et al., 2018). Increased precipitation and glacial melt reportedly favour decreased diatom dominance in nearshore waters, which would negatively impact exports. At the same time, warming and increased wind-driven upwelling associated with a more positive SAM may drive nutrient enrichment and increased diatom production and export (Boyd et al., 2015). These divergent trends are likely to vary regionally. They may be additionally impacted by a reduction in diatom size due to possible nutrient limitation from warming-induced increases in summertime stratification (Sallée et al., 2021; Thomalla et al., 2023). The myriad responses in community structure to multiple factors that are changing concurrently make it challenging to project the outcome of this biologically mediated feedback.

5.3.2.4 Phytoplankton Iron Stress

Seasonal changes in light, temperature, and micronutrients (e.g., iron) ultimately constrain (Martin, 1990; Boyd, 2002). Thus, changes to iron supply, availability, and demand collectively influence NPP, BCP, and climate trends. Many interactive bio-physicochemical processes influence iron cycling and determine its bioavailability (Boyd and Ellwood, 2010 NGEO). It remains unclear how warming and acidification will impact iron demand and accessibility (Tagliabue et al., 2023). ESMs generally predict increased regional NPP due to enhanced iron supply/accessibility and decreased biological demand (Tagliabue et al., 2023). Contemporary evidence supports increased iron supply from more frequent and intense storms and deepening summertime MLs (Sallée et al., 2021). However, indirect estimates of phytoplankton iron stress over the past two decades point instead to more stress and decreased NPP (Ryan-Keogh et al., 2023). These ambiguities hinder our ability to predict the role of the BCP under future ocean conditions and its role as climate feedback and so remain important topics of research.

5.3.2.5 Climate-Linked Fe-Supply Influences

Low NPP in iron-limited waters is contrasted to the more productive waters associated with dust deposition and upwelling at continental margins (5a vs 5b in Figure 5.7), highlighting how any climate-induced change to iron supply, availability, or demand may impact trends in NPP and the BCP and hence the carbon–climate feedback.

5.3.2.6 Particle Injection Pumps: Subduction and Obduction

Particle injection pumps are additional physical mechanisms that export organic carbon to depth (Bif et al., 2024). However, it is unclear how they will respond during the Anthropocene. For example, how will altered mixed-layer dynamics driven by warming, the SAM, ozone hole, and shifts in the westerly wind belts impact the magnitude of the mixed-layer pump? Similarly, how will climate-change-mediated alteration of the eddy field impact the eddy subduction pump (Llort et al., 2018) Although the response is unclear, these changes in downward carbon export from particle injection pumps may influence the magnitude of the BCP.

5.3.2.7 Fe Fertilization: Impact on Negative Emissions and Collateral Effects

The pivotal role of iron supply in setting regional NPP and influencing the BCP has driven discussion around the merits of purposeful ocean iron fertilization (OIF) of the SO (Martin, 1990). Mesoscale OIF in the subpolar and polar SO revealed enhanced NPP via diatom blooms, but whether this translates into more carbon export is unclear (Smetacek et al., 2012). Carbon transfer efficiency into AABW and air-sea CO_2 exchange constrains OIF efficacy, for which ESMs are best suited. Model projections by the Carbon Dioxide Removal Model Intercomparison Group, using a parameterization with an indirect OIF effect, report up to 1 Pg of carbon removal by purposeful OIF (mainly in the SO) (Keller et al., 2018). However, a recent modelling study (Tagliabue et al., 2023), with an improved ocean iron cycle representation, suggests minor carbon export or sequestration enhancement. Changes in atmospheric CO_2 in response to enhanced dust supply to much of the SO over centuries/millennia during the glacial terminations is likely <20 ppm. This is small compared to additional mechanisms, such as changes in ocean circulation, which contribute to the observed 80 ppm decrease (Sigman and Boyle, 2000). This potential impact of OIF equates to only a few ppm per century when the Vostok ice core record is examined in high resolution and matches the projection of Tagliabue et al. (2023), suggesting that the effect of OIF will be negligible.

5.4 Synthesis: the SO Carbon–Climate Feedback Fluxes on the ES: Past, Present, and Future

The SO is the carbon–climate fly-wheel of the planet. It connects with the ES through the atmosphere and the large-scale MOC. However, the ocean ML physics and biogeochemical processes modulate both the negative and positive feedback. It has been so in the past and present and projected to continue to be so under all emission scenarios. Changes in these feedback-linked processes (warming, freshening, ML stratification and depth, storm momentum fluxes, changing carbonate chemistry) in the SO are emissions scenario-dependent and projected to influence the decadal to centennial projections of global climate and ecosystem impacts under both positive and negative emission scenarios (Chikamoto and DiNezio, 2021; Ridge and McKinley, 2021).

While there is not yet any observable evidence of a carbon-concentration or carbon–climate feedback by the SO carbon cycle on the quasi-steady AF of anthropogenic CO_2 in the atmosphere (AF ±0.44%), there is rapidly growing evidence for changes to some of the processes and variability linked to carbon-concentration and carbon–climate feedback fluxes. Major advances in the past decade have been on the increasing confidence in the constraints and processes that influence the variability and trends of anthropogenic and natural CO_2 fluxes and storage (Hauck et al., 2020; Canadell et al., 2023). Here, we advocate that one of the most important gaps in understanding and projecting the feedback of the SO on global ES is in coordinated experimental observations and modelling the dynamics of the ML at the critical process dynamics scales. We understand the processes but do not yet understand or model the critical scales at which those processes interact to drive the fluxes across the atmosphere and ocean boundaries of the ML, particularly the base of the ML, which are the critical links to the ES.

These processes are critical for understanding the sensitivity of the SO to trends and variability in climate and the sensitivity of the global climate system to changes in the SO carbon cycle. Moreover, further ahead is the yet unconstrained and not well-understood influence of the SO on the global carbon-concentration and carbon–climate non-linear feedback under negative emissions (Zickfeld et al., 2016; Ridge and McKinley, 2021). Together, these feedback fluxes emphasize that the magnitudes and uncertainties for the variability and trends of anthropogenic and natural carbon fluxes in the SO cannot be understood or projected independently from the additional positive and negative feedback fluxes of the large planetary cycles of heat water, and wind momentum (Frölicher et al., 2015; Bronselaer et al., 2018; Williams et al., 2023; Menviel and Spence, 2024) (see Chapters 3 and 4).

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6

ANTARCTIC SEA-ICE

Ongoing Changes and Compelling Issues

Sharon Stammerjohn, Clare Eayrs, F. Alexander Haumann, Will Hobbs, Marika Holland, Phillip Reid, Lettie A. Roach, and Madison Smith

6.1 Introduction and Overview

Antarctic sea-ice is a highly sensitive integrator of coupled atmosphere–ocean processes (Figure 6.1) that define its regional, seasonal, and long-term variability. In turn, Antarctic sea-ice influences global climate variability through these same coupled processes (Chapter 2). The most obvious feature that defines the Antarctic sea-ice environment, and that sets it apart from its Arctic counterpart, is its geography (Thomas, 2017). Antarctica consists of a vast glaciated polar continent (~14 million km^2) surrounded by the great expanse of the Southern Ocean (SO) (Figure 0.1), a large portion of which is seasonally sea-ice covered each winter (~19 million km^2), while in summer only a small fraction of sea-ice persists year-round (~2–3 million km^2) (Stammerjohn and Maksym, 2017). Most of the seasonally sea-ice-covered ocean encompasses subpolar latitudes (~60–75°S), in contrast to Arctic sea-ice which straddles polar latitudes (~70–90°N) and is enclosed by surrounding landmasses. Thus, changes in seasonal solar insolation, winds, waves, and related feedbacks will be markedly different between these two polar regions.

Because there are no protective land masses in the SO for thousands of kilometers, the Antarctic sea-ice is exposed to some of the highest winds and waves on the planet and is forced by a range of atmospheric space/time scales, from quasi-weekly localized storms to seasonally variable quasi-stationary regional low-pressure systems, to the prevailing westerly wind circulation that twice-yearly contracts poleward to directly interact with the seasonally expanding and contracting Antarctic sea-ice cover. These atmospheric circulation patterns are also highly sensitive to, and modulated by, tropical, northern hemispheric, and global climate variability (Chapter 3).

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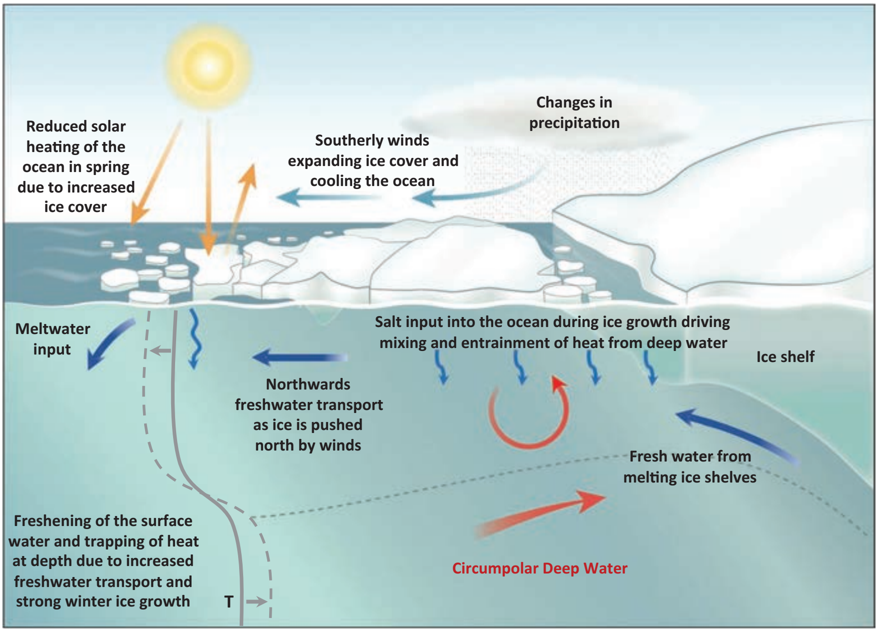

FIGURE 6.1 Schematic of several key atmosphere–ice–ocean interactions and feedbacks that would favor Antarctic sea-ice increases. (i) Enhanced cold southerly winds driving sea-ice growth and northward expansion. (ii) Reduced solar heating of upper ocean due to longer winter sea-ice seasons, shorter summer open water seasons. (iii) Increased freshening of upper ocean by increased precipitation to open ocean and sea-ice (that then melts in spring), and/or from melting ice-shelves. (iv) Increased ocean stratification reducing upward ocean heat flux due to surface freshening and/or ocean heat accumulation at depth due to strong winter sea-ice growth. (These processes in reverse would generally favour sea-ice decreases.) Orange arrows indicate solar heating or reflectance; red arrows, flow of subsurface warm water; blue arrows, flow affecting surface freshwater balance; and light blue arrows, air mass advection. Adapted from Maksym (2019).

But, this is only half the story: lurking below this very dynamic atmospherically driven surface environment is an equally dynamic ocean environment, with its complex of localized small-scale and fast-moving eddy circulation features, interacting with sub-mesoscale to regional ocean gyre circulations (Chapter 4). These ocean circulation features are in turn bordered to the south by the westward flowing coastal current, and to the north, by the eastward flowing Antarctic Circumpolar Current (ACC), the largest ocean current system on the planet (Chapter 4). Between these current systems, warm Circumpolar Deep Water (CDW) upwells in the divergent zone created by the prevailing westerly wind circulation (Figure 6.1). This oceanic heat source plays an important role in regulating Antarctic sea-ice

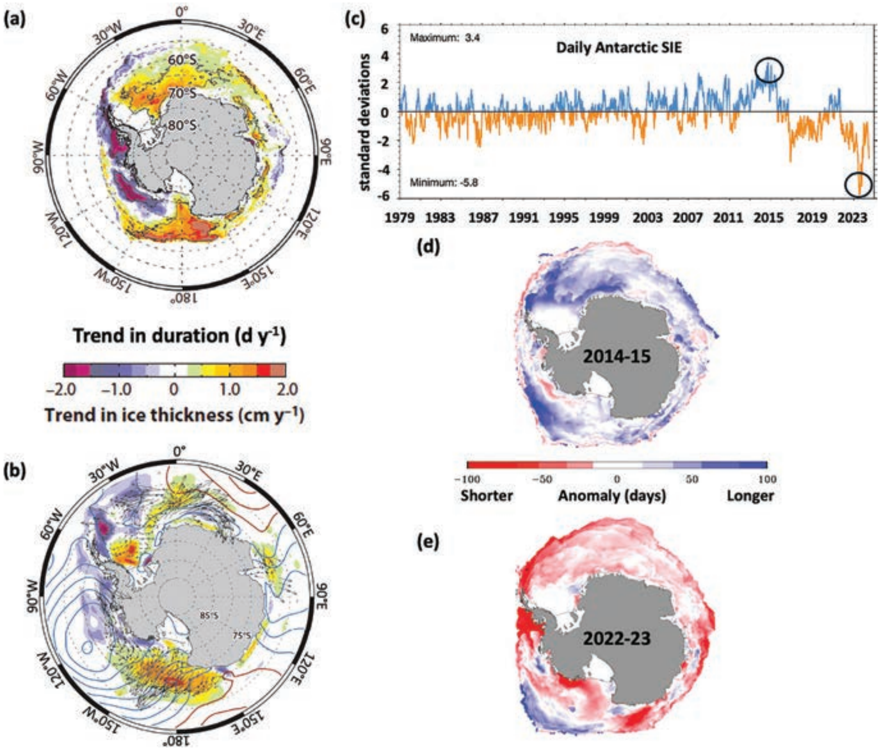

FIGURE 6.2 Satellite-observed changes in Antarctic sea-ice. (a) Sea-ice season duration trends (1979–2016), and (b) modeled May-June sea-ice thickness trends (Massonnet et al., 2013), overlaid with trends in satellite-observed sea-ice motion (arrows) (Kwok et al., 2017) and sea-level pressure (contours, 3 hPa y^{-1} intervals) for 1990–2009, showing strong coupling between changes in winds, sea-ice drift, thickness, and seasonality (adapted from Maksym, 2019). (c) Antarctic daily sea-ice extent from January 1979 to July 2023, showing standard deviations against the 1979–2022 mean, with years 2014–2015 and 2022–2023 highlighted. (d–e) Anomalies in sea-ice season duration (days) for 2014–2015 and 2022–2023 against the 1979–2022 mean.

thickness (as well as basal melt rates of the marine grounded portions of the Antarctic ice-sheet; Chapter 7) and is regionally and seasonally variable, while also prone to episodic variability in response to vertical mixing by wind-, eddy-, and buoyancy-driven processes (e.g., brine rejection during sea-ice formation).

When these different scales of space/time variability in the overlying atmosphere and underlying ocean (Figure 6.1) are combined and expressed through highly coupled processes (Figure 6.2a,b), one can appreciate how Antarctic sea-ice is a highly sensitive integrator of climate variability. The strong coupling with the atmosphere and ocean is what drives the growth and melt of Antarctic sea-ice, processes that in turn are affected by its relatively heavy snow cover and its subsequent deformation by winds, waves, and ocean currents.

In this chapter, we highlight current issues and outstanding questions, starting with recent Antarctic sea-ice changes within the context of satellite observations (Section 6.2), followed by what we currently know about competing thermodynamic and dynamic influences (Section 6.3.1), coupled wave–ice interactions (Section 6.3.2), competing surface versus subsurface influences (Section 6.3.3), and coupled feedbacks (Section 6.3.4). We also highlight what we currently know from simulating sea-ice processes (Section 6.4.1) and their drivers (Section 6.4.2) using fully coupled climate models. We then highlight key outstanding questions and future directions (Section 6.5).

6.2 Observed Sea-Ice Variability and Trends

For the large-scale assessment of Antarctic sea-ice, the most cited metric is circumpolar averaged Antarctic sea-ice extent (SIE), obtained from satellite-observed sea-ice concentration. A near-continuous daily record since 1979 (Figure 6.2c) shows an increasing SIE trend up to 2015 (Parkinson, 2019), with record winter maxima in 2014–2015 (along with widespread increases in sea-ice season duration, Figure 6.2d). After 2015, SIE then dropped considerably and remained anomalously low, with new record summer minima recorded in 2022–2023 (along with widespread decreases in sea-ice season duration, Figure 6.2e) (Reid et al., 2023).

The daily SIE record (Figure 6.2c) also shows a distinct increase in temporal variance and anomaly persistence starting ~2007 (Purich and Doddridge, 2023). Additionally, up until ~2015, there were distinct regional contrasts in SIE and seasonality trends (Figures 6.2a, 6.3b), which thereafter weakened (Figure 6.3a, c), especially between the Bellingshausen and Ross Sea regions (Figure 0.1), the latter consistent with how these regions respond to the Southern Annular Mode (SAM) and to tropical climate variability (Chapter 3).

The temporal shift in spatial anomaly patterns becomes apparent when comparing the daily SIE anomalies averaged over 2016–2022 to the 1981–2010 climatology (Figure 6.3c), which reveals mostly negative SIE anomalies since ~2015 across most Antarctic regions. This shift to a more widespread circumpolar anomaly pattern, together with the increase in temporal variance and persistence in SIE anomalies (Figure 6.2c), points to a change in atmosphere–ice–ocean interactions (Hobbs et al., 2024), possibly due to ocean changes at depth (Purich and Doddridge, 2023) (Section 6.3.3).

Another important type of sea-ice is landfast ice (or fast ice), which differs from seasonal sea-ice in that it is physically fastened to either icebergs or the coastline. Fast ice is an important platform for breeding emperor penguins and pupping Weddell seals (Chapter 9) and often influences polynya formation. Its climatological annual maximum is during October, comprising ~4% of the total October SIE. As with seasonal sea-ice, the circum-Antarctic trend in fast ice is relatively small (−0.19 ± 0.18% yr^{-1}, computed over 2000–2018 using MODIS satellite data) and consists of rather distinct regional trends (Fraser et al., 2023).

Both seasonal pack ice and fast ice play an important role in forming a protective barrier, or buffer, around the dynamically variable Antarctic coastal margin (Reid and Massom, 2022). Fast ice in particular absorbs and dampens high-energy long-period ocean swells that the SO is known for (Section 6.3.2). When this sea-ice barrier is removed, marine-terminating glaciers and floating ice-shelves become vulnerable to ocean waves and swell, increasing the probability of sudden disintegration (Massom et al., 2018). Antarctica's coastal glacial ice helps to stabilize Antarctica's interior ice-sheet, which comprises ~61% of the world's fresh water and represents ~58 m of potential sea-level rise (Fretwell et al., 2013).

Climatologically, coastal exposure (i.e., total exposed area along the coast, Figure 6.3d) occurs mostly in the summer months when SIE is at its annual minimum, with many coastal regions experiencing ice-free conditions for up to 50 days per year (Reid and Massom, 2022). Long-term trends in coastal exposure also show distinct regional variations, with the Bellingshausen Sea (inclusive of the western Antarctic Peninsula; Figure 0.1) recording an increase in ice-free days of 1–3 days yr^{-1} and the Eastern Weddell Sea and some East Antarctic regions recording a decrease in ice-free days of 1–2 days yr^{-1} over the 1979–2020 period (Reid and Massom, 2022). These long-term trends do not include the last two years (2022 and 2023) when large expanses of the Antarctic coastline were ice-free (Figure 6.3d). In fact, the lowest observed pan-Antarctic fast ice coverage of 123,200 km^2 (pers comm Alex Fraser) was observed in March 2022, indicating that at that time much of the Antarctic coastline was directly exposed to open ocean, and thus also to wind and wave forcing.

The coastal region is also often an area of high sea-ice production, and how changes in seasonal SIE affect coastal sea-ice production is still largely unknown, as are the related changes in sea-ice thickness. These and other factors are discussed in Section 6.3.

6.3 Observing Coupled Atmosphere–Ice–Ocean Processes

6.3.1 Competing Thermodynamic and Dynamic Influences

Changes in Antarctic sea-ice occur through the interplay between thermodynamic and dynamic processes (Figure 6.4). Dynamic processes refer to the movement and deformation of sea-ice due to external forces such as wind, waves, ocean currents, and internal stresses within the sea-ice cover. Thermodynamic processes relate to the exchanges of heat between the ocean and atmosphere that control local sea-ice freezing and melting. These processes can be tricky to separate in practice. The presence of sea-ice itself affects freezing (e.g., sea-ice impedes atmospheric

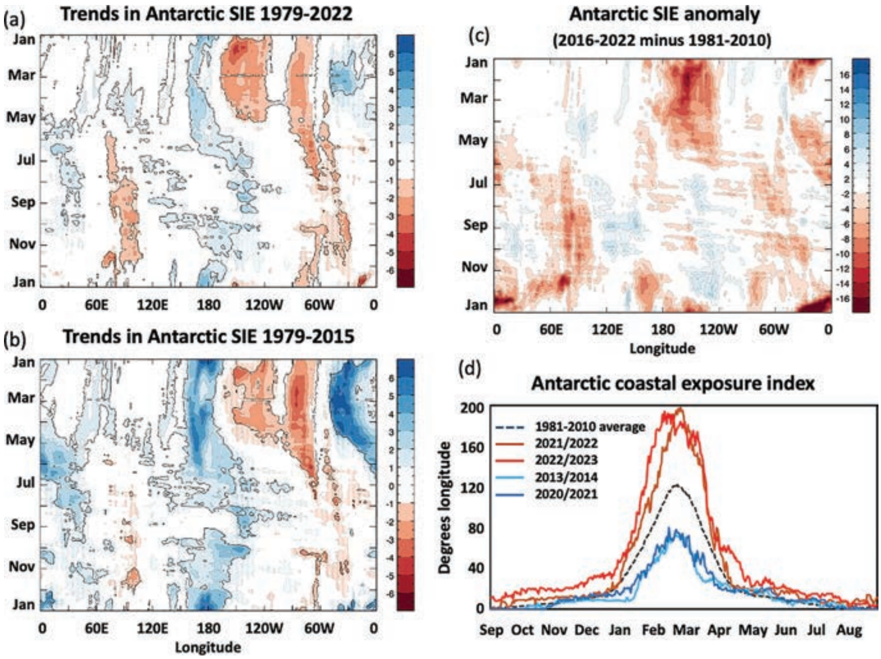

FIGURE 6.3 Concurrent space-time changes in Antarctic sea-ice. Hovmoller (time-longitude) diagrams of trends in Antarctic daily SIE standard deviation (yr^{-1}) over (a) 1979–2022 and (b) 1979–2015, the latter showing stronger positive trends (blue) with the exclusion of the more recent period. (c) Mean of daily SIE anomalies (km^2) averaged over 2016–2022 relative to the 1981–2010 climatology, showing the more recent shift to generally negative SIE anomalies. (d) Extremes in Antarctic coastal exposure measured in degrees of longitude for various time periods. Extended periods and regions of coastal exposure since 2021/2022 leave Antarctica's ice-shelves vulnerable to the effects of ocean waves and swell.

cooling of the ocean surface) and melting (e.g., due to its elevated albedo compared to ocean albedo), so dynamically changing the distribution of sea-ice also affects thermodynamic processes.

It is generally understood that thermodynamic processes have the most influence during the initial formation of sea-ice but also play a major role throughout most of the year. However, as the season progresses, the impact of winds becomes more important, especially when sea-ice melts and retreats (Eayrs et al., 2020). Himmich et al. (2023) demonstrate that the seasonal sea-ice zone can be divided into an "inner" region where freezing temperatures drive sea-ice growth and advance, and an "outer" zone (about a third of the total seasonal sea-ice zone) where sea-ice growth and advance are balanced between the import of sea-ice (from ice drift) and in situ melt. Himmich et al. (2023) further show that maximum summer mixed layer heat content describes most of the spatial variability in the timing of the subsequent autumn sea-ice advance for the inner zone (R^2=0.89), while the maximum summer mixed layer heat content is mostly described by the timing of the preceding spring ice-edge retreat (R^2=0.80). Kimura et al. (2023), using a slightly different analytical approach to distinguish thermodynamic from dynamic sea-ice processes and a much narrower "outer" band, found that thermodynamic processes were dominant almost everywhere, except during the sea-ice growth and advance season in the Amundsen Sea (150°W to 90°W), where the import of sea-ice into the outer zone, along with in situ melt, became important.

The primary difference between these two studies (Himmich et al., 2023; Kimura et al., 2023) is the different definitions used for the outer zone, which reflects a general lack of consensus on how to define what is otherwise known as the Antarctic marginal ice zone (MIZ), i.e., the dynamic interface between the

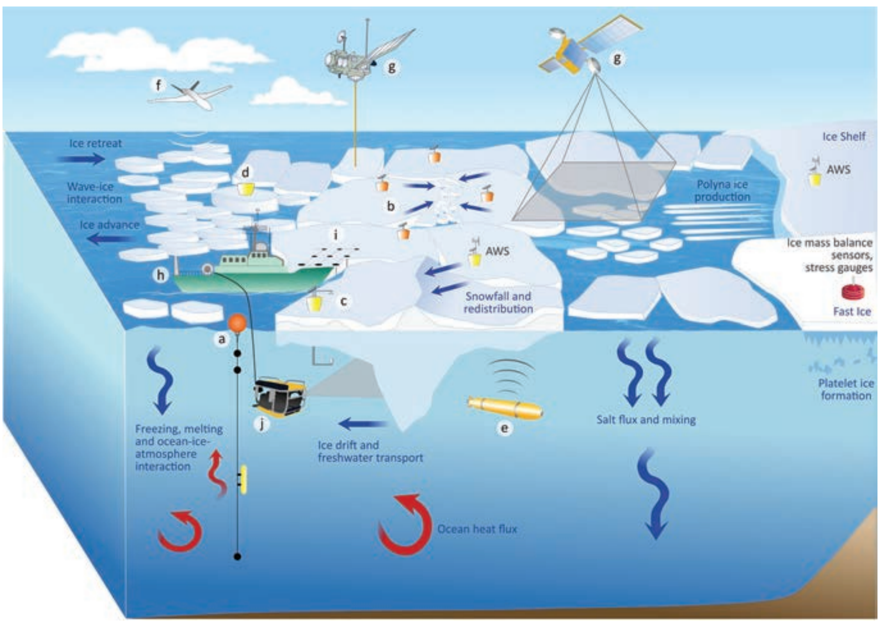

FIGURE 6.4 Conceptual view of thermodynamic influences (e.g., seasonal sea-ice growth/melt) versus dynamic influences (e.g., wind/wave/current-induced sea-ice drift, convergence/divergence, and advection of air/ocean thermal anomalies). Also shown are critically important observing platforms including (a) high-resolution ocean sensors on drifting buoys, (b) sea-ice deformation arrays, (c) sea-ice mass balance buoys and snow arrays, (d) wave buoys, (e) autonomous underwater floats/vehicles, (f) airborne vehicles, (g) satellite radar/radiometers/altimeters for sea-ice concentration/drift/thickness, (h) ship-based observations, (i) on-ice sampling, and (j) ship-deployed ocean sampling. Adapted from Newman et al. (2019).

open ocean and ice-covered ocean. The MIZ has markedly different properties to the more consolidated inner sea-ice cover due to the relatively stronger influence from wind and waves in the MIZ (Section 6.3.2) (Bennetts et al., 2022), which is also typically characterized by a younger, thinner, less snow-covered sea-ice. The more consolidated inner sea-ice cover is generally thicker and more heavily snow-covered, while also interspersed by heavily ridged and rafted sea-ice and/or thin openings (i.e., leads) caused by convergence or divergence within the pack ice (Figure 6.4).

If we are to understand sea-ice variability, it is paramount that we identify these distinctly different regions subject to different combinations of multi-scale dynamics. For example, the width of the MIZ is ideally defined by a fundamental length scale, but to date there is no clear approach for defining a MIZ length scale, and different methods can lead to contrasting MIZ characterizations (Dumont, 2022). Traditionally, the MIZ has been defined as the zone just inside the ice edge with sea-ice concentrations ranging between 15% and 80%, and where open sea-ice drift is assumed (Squire, 2020). This definition has been shown to be an effective approach for Arctic sea-ice studies but less effective around Antarctica, where sea-ice type is unrelated to sea-ice concentration, or where wave penetration and free-drift conditions have been observed in 100% sea-ice cover (Vichi, 2022).

In short, the challenge of distinguishing thermodynamical from dynamical influences in driving sea-ice variability is largely due to our current inability to accurately resolve sea-ice type and thickness from satellite observations, especially for snow-laden sea-ice that has been dynamically thickened through sea-ice drift and deformation processes (Maksym, 2019). Further, without better knowledge of how Antarctic sea-ice thickness is changing, either seasonally or regionally or over the long term, it also hampers our understanding of how Antarctic sea-ice responds to ongoing forced changes.

6.3.2 Competing Wave–Ice Interactions

The often-competing interaction of ocean surface waves with sea-ice has long been acknowledged as a key driver of Antarctic sea-ice processes (Wadhams et al., 1987). Coupled wave–ice interactions have become an important area of focus in recent years in tandem with advancements in observational and modeling approaches (Sections 6.3.4 and 6.4.1). The wave-impacted area of the sea-ice zone is often within the MIZ and is typically determined by the rate of wave attenuation. Wave attenuation is dependent on sea-ice properties (Squire, 2020), especially sea-ice thickness (Rogers et al., 2021). Waves tend to attenuate in the first 10–20 km from the ice edge but can also be generated in partial sea-ice cover (Ardhuin et al., 2020) with a notable impact on the extent of the wave-impacted area (Figure 6.5a). However, the wave-impacted sea-ice area is still poorly constrained, largely due to wave growth dependencies on variable wind inputs over different sea-ice types and concentrations (Cooper et al., 2022). Wave-impacted areas can also include coastal (latent heat) polynyas, where strong katabatic winds can result in significant wave growth over a relatively short open water distance (fetch). How wind and waves affect polynya sea-ice production, and hence bottom water production, is also an active area of research (Section 6.3.3, Chapter 4).

In situ methods to measure wave attenuation typically involve pairs of wave buoys deployed within the MIZ, or with one of the two wave buoys just outside the MIZ (e.g., Kohout et al., 2020). Wave parameters can also be quantified from radar and optical satellite methods, which allows spatial estimates of wave attenuation (e.g., Collard et al., 2022). Radar methods including synthetic aperture radar can resolve spatial wave patterns in stunning resolution unrestricted by cloud conditions (Stopa et al., 2018), and methods to retrieve quantitative wave parameters are improving (Collard et al., 2022). Additionally, recent advances in satellite altimeters such as ICESat-2 have allowed estimates of wave attenuation over larger areas (Brouwer et al., 2022) but are dependent on cloud-limiting effects. Laboratory studies using lab-grown sea-ice, or buoyant objects used as proxies for sea-ice, can isolate the impact of various sea-ice characteristics on attenuation rates not yet achievable with in situ field methods (Herman et al., 2019) but are inherently limited by the wave tank size and thus the scale of achievable wavelengths (Squire, 2020).

The propagation and generation of waves across large parts of the Antarctic sea-ice zone impacts not only sea-ice formation processes but also floe size distribution (FSD). FSD is a description of the geometric variability of floes within the sea-ice cover and is characterized by a probability distribution of floe diameters, which evolve seasonally through sea-ice formation and melt. A given FSD determines the effect of waves on atmosphere–ice–ocean interactions, including on the properties of the sea-ice itself (e.g., freezing/melting rates, rheology, and mechanical strength) (e.g., Smith et al., 2022). Floe sizes can be measured from ship-based observation, helicopter, satellite imagery, and, more recently, satellite altimetry. However, floe size observations are still difficult to obtain across all relevant spatial and temporal scales, thus challenging our ability to properly characterize and model FSD (Section 6.4.1).

When waves are present during initial seasonal sea-ice formation, frazil crystals accumulate into slushy disks of sea-ice referred to as pancake ice (Shen et al., 2001). The pancake ice is so-called because of raised edges caused by wind/wave-driven collisions of pancake ice floes, which can also lead to pancake rafting (Squire, 2020). The transition from pancake ice during initial sea-ice formation to a more consolidated sea-ice cover begins with the welding of floes (Roach et al., 2018). Recent ship-based observations of floe sizes in the Antarctic MIZ during freeze-up showed two distinct peaks indicative of pancake ice formation and welding as key controls on FSD (Alberello et al., 2019). Yet, modeling studies have also emphasized the importance of welding and ice "healing" in driving broad-scale floe size and thickness evolution as well (Section 6.4.1) (Roach et al., 2019).

At the other end of the sea-ice life cycle, feedback between wave heights and floe size may impact and even accelerate the spring sea-ice meltback. Large waves

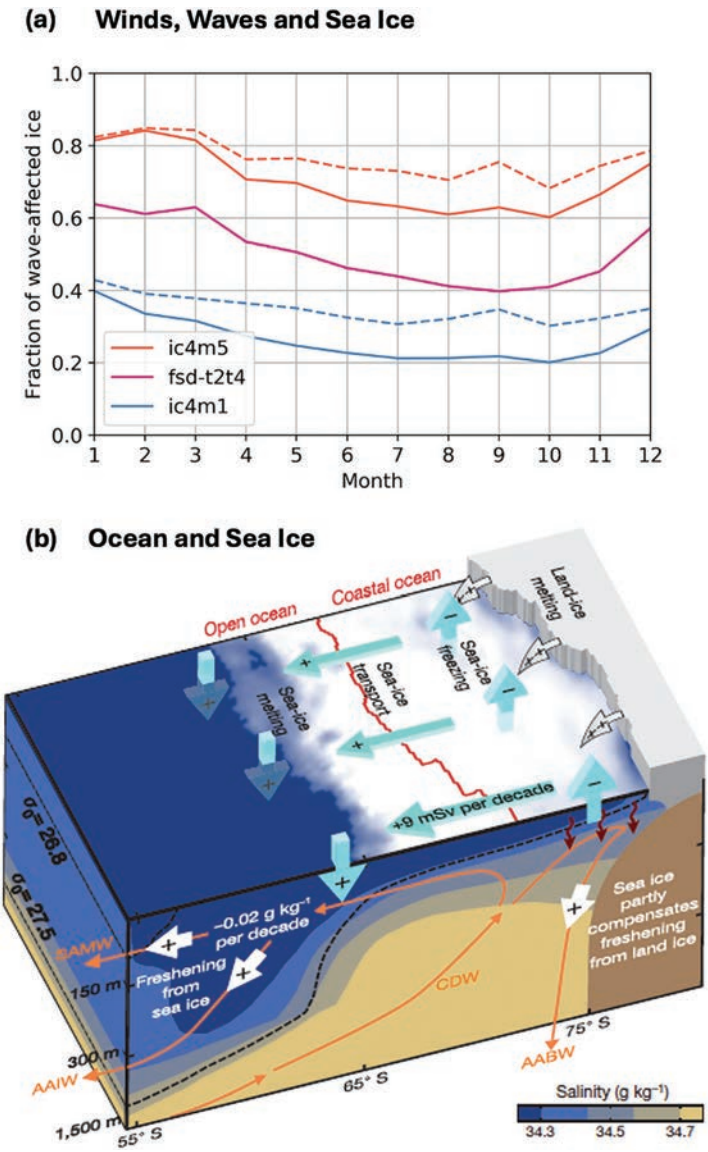

FIGURE 6.5 Winds, waves, ocean, and sea-ice. (a) Coupled wind/wave/ice interactions: monthly mean fractional area of the Antarctic sea-ice cover that is wave-affected in three global wave–ice model experiments for 2018 (adapted from Cooper et al., 2022). The standard experiment (solid lines) reduces wind input to zero as SIC approaches 100%. The wind-enhanced experiment (dashed lines) reduces wind input to 50% as SIC approaches 100%. (b) Coupled ocean/ice interactions: schematic showing the effect of sea-ice processes on water mass transformation (fluxes), ocean circulation (orange arrows), and freshwater transport (cyan arrows) (Section 6.3.3). Background shows mean salinity (color scale) and density (dashed black lines) separating Circumpolar Deep Water (CDW) from Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW). AABW, Antarctic Bottom Water. Adapted from Haumann et al. (2016).

from the SO can fracture or break sea-ice floes hundreds of kilometers from the ice edge (Kohout et al., 2014). Floe size, along with mechanical properties of sea-ice, is a strong control on wave energy dissipation (Ardhuin et al., 2020) and, thus, wave fracture (Voermans et al., 2020). The resulting fracture into smaller floes allows the propagation of waves further into the sea-ice cover. In short, many questions and challenges remain regarding coupled wave–ice interactions and their often-competing effects on Antarctic sea-ice processes (Sections 6.3.1 and 6.4.1) and feedbacks (Section 6.3.4).

6.3.3 Competing Surface and Subsurface Influences

Underlying most of the Antarctic seasonal sea-ice zone is warm and salty CDW (Figures 6.1, 6.5b) (Chapter 4). These warm waters are located only a few hundred meters below the sea-ice cover, with the potential, if brought to the surface, to melt large amounts of sea-ice from below during austral winter. The only factor that keeps the CDW from melting sea-ice is that relatively fresh surface waters induce a marginally stable density-stratification, even when the surface ocean reaches the freezing point in winter. The unique combination of a weak halocline with wind-driven upwelling of warm deep waters yields a large potential for the ocean to interact with Antarctic sea-ice and drive variations in the sea-ice growth (Martinson and Ianuzzi, 1998).

A number of freshwater sources help maintain this near-surface halocline, notably precipitation and meltwater from icebergs, ice-shelves, and glaciers. The most significant freshwater flux in the polar SO though is the freeze and melt cycle of sea-ice itself (Figure 6.5b) (Haumann et al., 2016; 2020). When seawater freezes (with a nominal salinity of 34 g kg^{-1}), most of the salt in the seawater is rejected as brine. This process of freezing and brine rejection leaves behind a moderately fresh sea-ice cover (with bulk salinity nominally ranging from 5 to 10 g kg^{-1}) and a saltier underlying ocean. Throughout fall and winter, the formation and expansion of the sea-ice cover, which also captures any falling snow, progressively makes the underlying ocean more and more saline. Eventually, the seasonal progression of brine rejection, together with heat loss to the atmosphere, serves to destratify the upper ocean and leads to deeper and deeper mixing as winter progresses. When this mixing reaches a sufficient depth, warm CDW can be entrained into the surface layer, albeit sporadically (Saenz et al., 2023). The resulting upward injections of warmer sub-surface water thin sea-ice from below. The associated release of freshwater from the basal melting of sea-ice restratifies the water column, ceasing the subsurface heat release. This process is thought to substantially limit the growth of sea-ice in the southern hemisphere and is partly why Antarctic sea-ice is substantially thinner and more seasonally confined than its Arctic counterpart (Wilson et al., 2019). In contrast, the Arctic Ocean is not only at higher latitudes than the SO but is also more strongly stratified by considerably larger amounts of freshwater inputs from the numerous rivers draining into the Arctic Ocean (Turner and Overland, 2009; Carmack et al., 2016).

While the release of subsurface heat due to destratification potentially limits the growth of sea-ice seasonally, its interannual to multidecadal variations might imprint on long-term sea-ice variability. However, the amount of heat released from CDW to the surface during deep wintertime mixing has been challenging to quantify due to a lack of ocean observations under an actively growing and evolving winter sea-ice cover. The types of ocean observations needed are also challenging to acquire and include high-resolution vertical profiles and fine-scale turbulence measurements (Figure 6.4) to best resolve the small temporal and spatial scales involved in the destratification process. Without a doubt, the competing effects of surface-induced stratification that favors sea-ice growth (inclusive of surface freshening from increases in precipitation and/or increases in glacial meltwater inputs) versus subsurface heat release that limits (or reduces) sea-ice growth, yield a complex interplay involving both positive and negative feedbacks (Section 6.3.4).

A further complication is the fact that there is a net annual northward transport of sea-ice in the SO due to the prevailing atmospheric circulation (Figure 6.5b) (Haumann et al., 2016). The net northward transport causes a sea-ice-induced net salinification inshore and net freshening offshore, thus causing greater destratification and subsurface heat release inshore, but increased stratification and subsurface ocean heat retention offshore (Haumann et al., 2020). How these ice–ocean processes are potentially driving the interannual to multidecadal variability in ocean heat content and sea-ice in the SO is currently unknown. For example, at the time of this writing, it is unclear to what degree these ice–ocean processes and feedbacks contributed to the satellite-observed sea-ice expansion (1979–2015), but there are strong indications that the ocean has contributed to recent declines and increased variability (Purich and Doddridge, 2023, Hobbs et al., 2024). The development of a more robust understanding of the connection between sea-ice and the subsurface ocean is at the forefront of current research activities (Chapter 4).

6.3.4 Coupled Sea-Ice Feedbacks

Sea-ice feedbacks around Antarctica are complex, and depending on the feedback mechanism, can vary in space and time, making it challenging to fully assess their impacts either from observations or coupled climate models (Goosse et al., 2018). The most well-described feedback is the snow and ice albedo positive feedback. Until recently (~2015), Antarctica (in contrast to the Arctic) has generally played an offsetting (negative) role in the global annual snow and ice albedo feedback. But, with the substantial Antarctic sea-ice losses post-2015 (Section 6.2), it now plays an increasingly positive role (Riihelä et al., 2021). During the austral spring and in areas where the sea-ice cover is broken-up by wind-, wave-, and/or current-driven sea-ice motion, the lower-albedo open ocean absorbs more solar radiation, which in turn drives more bottom and lateral melt of the broken-up sea-ice floes, thus causing a strong sea-ice albedo positive feedback (Eayrs et al., 2019).

For Antarctic sea-ice, the strength of the sea-ice albedo feedback in spring might well be amplified by high wind and waves that characterize the SO, which in turn may explain the asymmetry observed in the Antarctic mean annual sea-ice cycle, with its shorter period of spring-summer sea-ice melt (~October to February, five months) versus its longer period of autumn-winter sea-ice growth (~March to September, seven months) (Eayrs et al., 2019). Although wave action can create a positive feedback in spring-summer, in winter wave action can lead to enhanced sea-ice production in newly created open water areas, thus limiting further wave action (i.e., negative feedback). However, due to limited data either from field observations or wave-resolving ocean–ice coupled models, only a handful of studies have examined the positive wave–ice feedback in summer (Li et al., 2021), and there are even fewer studies analyzing the negative wave–ice feedback in winter (Horvat, 2022).

The sea-ice-albedo feedback is also linked to another seasonal feedback, the ocean–sea-ice thermal feedback (Himmich et al., 2023). This seasonal feedback happens when an earlier (later) spring sea-ice meltback allows greater (lesser) absorption of solar heat by the upper ocean, which in turn causes the timing of autumn sea-ice growth to be relatively later (earlier) given that it takes more (less) time to cool a surface mixed layer that has a relatively higher (lower) ocean heat content.

Clouds also play a major role in driving sea-ice variability by influencing the energy balance, but in general, cloud feedback processes are difficult to measure. The interactions between clouds, radiation, and sea-ice are complex and are a leading source of uncertainty in global climate models (Bretherton, 2015). Nonetheless, it is known that the sea-ice cover affects the occurrence and properties of clouds (Adhikari et al., 2012), as well as the concentration of aerosol particles (Liu et al., 2012), which influences cloud nucleation and cloud properties. Changes in cloud cover and properties can impact the radiative interactions between clouds and sea-ice, affecting the energy available for sea-ice growth or melt. Positive feedback occurs when sea-ice melts particularly during non-summer months, and surface turbulent heat fluxes over the open ocean increase humidity and low-level clouds (Goosse et al., 2018). The subsequent increased downwelling radiation leads to further sea-ice loss.

As described in Section 6.3.3, there is also a negative ice–ocean feedback in areas where, typically by mid-winter, any additional sea-ice production causes entrainment of warm CDW at depth, leading to decreased sea-ice production and thinning of the winter pack ice from basal melt (Saenz et al., 2023). However, there can also be positive ice–ocean feedback in areas where vertical exchanges from sea-ice production lead to a net storage of heat at depth, favorable for sustained sea-ice production (Lecomte et al., 2017), albeit at slower rates for thicker sea-ice due to a diminishing conductive heat flux with thicker sea-ice.

Many of the feedbacks described here can interact at different times or in different areas, thus differently influencing the seasonal and regional distribution of Antarctic sea-ice, as well as its response to external forcing. Additionally, snow on sea-ice can also amplify or dampen both the atmosphere-ice and ocean–ice feedbacks, with snow thickness playing a large role in defining the feedback. The snow cover on Antarctic sea-ice can be sufficiently thick to depress the freeboard, causing seawater flooding at the snow/ice interface that leads to snow-ice formation (Maksym and Markus, 2008). However, being able to observe and quantify snow thickness on Antarctic sea-ice remains elusive due to its high temporal and spatial variability (Sturm and Massom, 2017), often caused by very localized snowfall events and the subsequent redistribution of fallen snow by winds.

6.4 Modeling Coupled Atmosphere–Ice–Ocean Processes

6.4.1 Sea-Ice Processes in Fully Coupled Climate Models

Fully coupled climate models are essential tools for understanding how climate variability affects Antarctic sea-ice and its future projections. Recent modeling work has focused on better resolving sea-ice thickness, snow on sea-ice, surface albedo, and wave–ice interactions.

The area covered by a sea-ice model grid cell can contain many types of sea-ice and sea-ice thicknesses. How sea-ice thickness evolves in coupled climate models depends heavily on how the ice-thickness distribution is defined for each grid cell (Hunke et al., 2010). With advances in computer power and architecture, it is now possible to run climate simulations at high resolution in the polar regions. Discrete element sea-ice models that resolve individual floes are being explored (Turner et al., 2022), and although currently computationally expensive, they may provide an exciting path forward for sea-ice modeling in the future.

Simulated surface albedo depends on the fractional coverage of different surface types (bare sea-ice, melt ponds, snow cover, and open water). Many models use complex radiative transfer calculations (Briegleb and Light, 2007) and compute albedos using specified optical properties for these surface types. Work is underway to improve the representation of different surface types, their optical properties, and spectral resolution. Snow, with its high albedo, is particularly important, and ongoing work aims to better capture snow spatial distributions and thermal properties (Lecomte et al., 2013).

Ocean surface waves can have strong, non-linear interactions with the sea-ice cover and may play a role in melt and growth feedback (Sections 6.3.2 and 6.3.4). Coupled wave–ice models are beginning to emerge and suggest that a substantial fraction of sea-ice can be affected by waves (e.g. Roach et al., 2019). Representation of wave–ice interactions requires resolution of the sea-ice FSD, which is determined by a complex interplay of physical processes. More observations are required to better understand and constrain the relevant processes, especially wave attenuation. The computational expense of spectral wave models presents an additional challenge.

Given these challenges, as well as challenges in the representation of the ocean and atmosphere, it is not surprising that simulation of Antarctic sea-ice remains an issue for many of the ~40 models in the latest (Phase 6) Coupled Model Intercomparison Project (CMIP6).

Although there have been modest improvements in intermodel spread and the regional distribution of sea-ice, many models still simulate implausible mean sea-ice area (Roach et al., 2020). The observed sea-ice expansion prior to ~2015 is very rarely captured by CMIP6 models (Figure 6.6a) and none reproduce the observed spatial pattern of sea-ice concentration trends during this period (Shu et al., 2020). It is also extremely unlikely that CMIP6 models capture negative anomalies as large as those observed during 2023, even when including strong climate forcing (Diamond et al., 2024). Further, the high-frequency variability of SIE still tends to be biased low (Blanchard-Wrigglesworth et al., 2021a). One issue is that the modeled upper SO remains biased warm and fresh relative to observations (Beadling et al., 2020), and most are unable to capture the observed sea surface temperature (SST) trend (Wills et al., 2022). However, the representation of the ACC is improved compared to previous generations (Beadling et al., 2020), and the position, strength, and variability of the extra-tropical westerly wind jet over the SO is also better captured (Bracegirdle et al., 2020).

A number of recent studies shed light on the different processes driving simulated Antarctic sea-ice trends during the sea-ice expansion phase (Figure 6.6b). These studies have variously constrained coupled climate models to simulate observed SO SSTs, observed winds, observed sea-ice drift, observed estimates of meltwater from the Antarctic ice-sheet and its ice-shelves, or combinations thereof. As shown in Figure 6.6b, these constrained simulations better capture the observed Antarctic sea-ice increases than their free-running counterparts. Qualitatively similar impacts from adding Antarctic meltwater are found in several CMIP6 models (Swart et al., 2023).

Other work has emphasized the importance of ocean mesoscale eddies, which are the dominant mechanism of heat transport across the ACC (Chapter 4). Eddy-permitting simulations exhibit lower poleward heat transport than non-eddy-permitting simulations in response to external forcing, delaying Antarctic sea-ice decline (Figure 6.6b). The model-observation discrepancy may also reflect undersampled ocean multidecadal variability, rather than a bias (Singh et al., 2019).

Taken together, these studies highlight that many different factors are at play in the complex Antarctic climate system. The improvements obtained by correcting biases in the atmosphere and/or ocean suggest that these components may be largely responsible for the underestimation of observed Antarctic sea-ice expansion. However, more work is required to tease apart the drivers of coupled model biases, especially in the current phase of Antarctic sea-ice decline.

6.4.2 Drivers of Antarctic Sea-Ice Variations from Large-Scale Modeling Experiments

Despite widespread biases in the simulation of Antarctic sea-ice, some models simulate a reasonable annual cycle and realistic sea-ice concentrations (Holmes et al., 2019). Models also capture the observed asymmetric timing of the Antarctic sea-ice maximum and minimum extent, although this is unsurprising given that it appears the

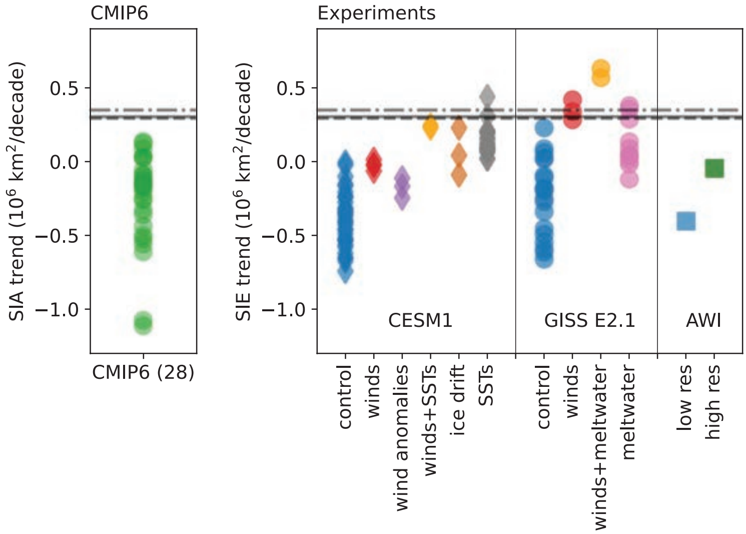

FIGURE 6.6 1990–2015 Antarctic sea-ice trends in (markers) climate models and (horizontal gray dashed lines) observations from NSIDC version 4 Climate Data Record, NASA Team, and Bootstrap observations (Meier et al., 2021). (a) Sea-ice area (SIA) trends in 28 CMIP6 models, with one ensemble member per model (Roach. 2020). (b) Sea-ice extent (SIE) trends from process experiments. CESM1: wind, CESM1: wind anomalies, and CESM1: wind+SSTs are from Blanchard-Wrigglesworth et al. (2021b). CESM1: ice drift is from Sun and Eisenman (2021). CESM1: SSTs are from Zhang et al. (2021). GISS: wind and GISS: wind+meltwater are from Roach et al. (2023) and GISS: meltwater is from Schmidt et al. (2023). AWI: low-res and AWI: high-res show non-eddy-permitting and eddy-permitting configurations from Rackow et al. (2022). Some experiments in (b) use CMIP5 forcing while others use CMIP6 forcing; see the respective references for full details. We thank all cited authors for sharing their model output.

asymmetry largely arises from the seasonal cycle of insolation (Roach et al., 2022) and is relatively insensitive to changes in sea-ice physics (Goosse et al. 2023).

Additionally, some individual models simulate realistic relationships between atmospheric circulation and sea-ice variations. For example, many models simulate a reasonable seasonal lagged response of Antarctic sea-ice area to summertime SAM variations (Polvani et al., 2021) (Chapter 3), and some models realistically capture the spatial distribution of related sea-ice anomalies (Landrum et al., 2017). Longer lagged relationships, such as the observed influence of October wind variations on the following March sea-ice cover in the western Ross Sea (Holland et al. 2017a), are also captured in some models (Figure 6.7a–c). Notably, though, the internal variability of the Antarctic climate is large and affects the strength and spatial characteristics of these relationships. For example, as revealed by analysis of individual ensemble members from the same model (Figure 6.7b–c), different 1979–2015 realizations exhibit different lagged correlations. Hence, there is value in single-model large ensembles that allow for the exploration of the influence of internal variability on these relationships. Activities, such as the initial-condition multi-model large ensemble (MMLE; Deser et al., 2020), enable the separation of model structure and internal variability and hold promise for a better understanding of how these factors influence simulated drivers of Antarctic sea-ice variations.

Other modeling studies have provided insights on Antarctic sea-ice variability across timescales. For example, initialized predictability studies (Bushuk et al., 2021) indicate that the sea-ice and ocean states have considerable memory that influences sea-ice variations on seasonal to interannual scales. During the sea-ice advance season, sea-ice area anomalies persist for several months due in part to long-lived SST anomalies that the sea-ice encounters as it expands equatorward. However, this sea-ice persistence is lost during the spring as sea-ice melts southward into regions with little SST memory. These processes result in low summer sea-ice area predictability but a reemergence of predictability during the fall and winter, which can act on multi-year timescales (Figure 6.7d). Ocean mixed layer dynamics also play a role as ocean heat content anomalies can be stored below the shallow summer mixed layer but then resurface as the mixed layer deepens in the fall (Libera et al., 2022).

Modeling studies have also suggested an important role of the SAM and the Amundsen Sea Low (ASL) (Chapter 3) in driving a two-timescale response in sea-ice variability. Ferreira et al. (2015) showed that in response to a positive SAM anomaly (thus, stronger westerlies), modeled sea-ice and SST had a fast response associated with increased equatorward Ekman transport that resulted in increased sea-ice and cooler SO SSTs. However, on longer timescales, increased upwelling of deeper and warmer waters occurred, resulting in sea-ice decline. Comparisons across CMIP5 simulations (Holland et al., 2017b) indicate that many models simulate this two-timescale response, but there are considerable discrepancies across the models on the magnitude and timescale of the response. These discrepancies are in part due to differences in simulated climatological ocean conditions, which affect how wind variations modify lateral and vertical ocean heat transport (Kostov et al., 2017). Given that SAM variability projects onto variability in the ASL, sea-ice anomalies (and the two-timescale response) are not uniform around the continent, with the Weddell Sea dominating the long-term sea-ice loss in CMIP5 models (Holland et al., 2017b).

6.5 Outstanding Questions and Future Directions

In considering the focus of future Antarctic sea-ice research, we expect that understanding extreme sea-ice variability will be a leading topic. Prior to the recent decline in Antarctic sea-ice observed since the austral spring of 2016, most research focused on the observed positive trend in Antarctic sea-ice, a trend that

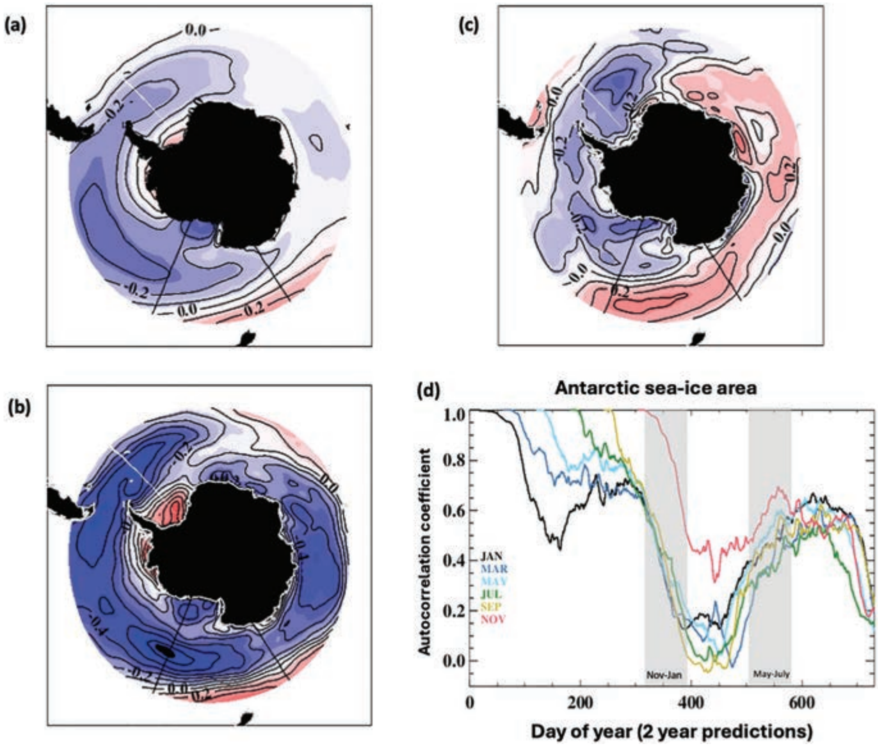

FIGURE 6.7 Correlation of 1979–2015 October zonal winds with the following March sea-ice in the 150–200E region (indicated by the black straight lines) from the CESM2 Large Ensemble for (a) all 50 ensemble members, (b) Ensemble member 18, and (c) Ensemble member 24; the lined contour interval is 0.1 with negative correlations in blue and positive correlations in red. (d) Anomaly Correlation Coefficient of the daily Antarctic sea-ice area from initialized predictions with CESM2. The simulations are run in a "perfect model" framework in which the model is initialized with conditions from simulated historical integrations in the year 2010. Six different initialisation timings are considered (on the first of Jan, March, May, July, Sept, and Nov, shown in the different colored lines). For each initialisation, 70 ensemble members are performed.

has been largely attributed to a combination of internal variability (Polvani and Smith, 2013) – in particular tropical decadal variability (Chapter 3) – and the ocean's damping effect on the surface response to climate change in the high latitude Southern Hemisphere (Armour et al., 2016; Chapter 4).

It is important to note that the high internal variability of Antarctic sea-ice presents significant challenges for detecting any forced responses (Hobbs et al., 2015). Even in the relatively short satellite record, pronounced modes of variability have been found to be transient. That said, the observed increase in temporal variance and persistence, as well as spatial coherence observed since ~2007, are indeed indicators of an impending abrupt critical transition, or regime shift, based on dynamical systems theory (Hobbs et al., 2024). By regime shift, we mean specifically a change in the sea-ice response to atmospheric and oceanic drivers; it does not necessarily imply an anthropogenic change or irreversible "tipping point".

While there is no consensus yet on the cause(s) of the observed Antarctic sea-ice regime shift, it is interesting to consider some potential physical drivers of this shift. The atmosphere is undoubtedly a primary source of sea-ice variability at interannual and shorter timescales, and studies have shown the importance of the atmosphere in the initial rapid sea-ice loss in 2016 (Eayrs et al., 2021, Wang et al., 2019). Despite the importance of large-scale atmospheric modes (Chapter 3), these modes do not exhibit changes that immediately explain the observed changes in sea-ice variance and persistence (Hobbs et al., 2024). Further, while sea-ice anomalies have become more spatially homogeneous, the atmosphere has become more spatially heterogeneous (Schroeter et al., 2023). Hence, while the atmosphere is an essential driver of individual events such as the rapid 2016 sea-ice loss, it appears that the atmosphere alone is insufficient for explaining the more systemic changes in spatial/temporal variability since ~2007. This suggests that the sea-ice–ocean system has changed in its response to atmospheric forcing. Concurrently, studies also show a build-up of ocean heat in the SO since at least ~1980 (Cheng et al., 2023), with additional evidence showing increases in upper ocean heat anomalies just north of the Antarctic sea-ice zone coincident with increases in sea-ice anomalies (Purich and Doddridge, 2023).

The sea-ice response to ocean changes is not nearly as immediate or evident as for the atmosphere, but, nevertheless, the SO is an important constraint on the sea-ice response (Section 6.3.3). Research has shown anthropogenic CDW-warming and surface freshening in the high latitude SO (Hobbs et al., 2021), which has implications for sea-ice–ocean feedbacks (Section 6.3.4; Chapter 4). A warmer CDW would increase vertical heat flux during winter, potentially resulting in a thinner (and more easily melted) sea-ice cover, but this effect is counteracted by surface freshening and its related increased stratification (Purich et al., 2018). It is unknown which is the dominant effect. It should also be noted that the surface freshening trend has reversed since 2016 (Silvano et al., 2024), simultaneous with extreme low sea-ice states. Ocean–sea-ice feedbacks impact not just the mean state of sea-ice but also its variability. For example, the winter entrainment of old deep water into the mixed-layer explains the loss of ocean–sea-ice memory from one summer to the next (Section 6.4.2) (Libera et al., 2022). Observed increases in sea-ice memory are further evidence that the ocean could be an increasingly important driver (Hobbs et al., 2024).

Many of the unanswered questions highlighted above and throughout this chapter point to research priorities that emerge as key future directions.

1 Increase collaborative, interdisciplinary, and multi-platform sea-ice field studies (Ackley et al., 2020) and expand year-round autonomous atmosphere–ice–ocean observations (Newman et al., 2019; Figure 6.4).
   a) Targeted process studies to improve understanding of how atmosphere–ice–ocean interactions respond to episodic forcing.
   b) Fine-scale ocean turbulence measurements under actively growing and melting sea-ice to improve understanding and quantify the influence of ocean heat on Antarctic sea-ice thickness.
   c) Wave–ice process studies to improve understanding of effects on sea-ice production, thickness, and FSDs.
   d) Coastal process studies to improve understanding of how atmosphere–ice–ocean interactions moderate glacial ice mass changes.
2 Improve satellite-derived retrievals of snow and sea-ice thickness, drift, deformation, and FSD to better quantify space/time variability in sea-ice production/thickness/deformation and consequent contribution to volume and concentration changes.
3 Improve parameterizations of key atmosphere–ocean–ice interactions not yet captured or resolved in coupled climate models (e.g., waves, clouds, localized katabatic winds, polynya dynamics, meltwater inputs) to improve both hindcasts and future projections, as well as seasonal to decadal prediction of Antarctic sea-ice variability and change.

Throughout this chapter, we highlighted the multiple drivers of Antarctic sea-ice variability, and at this stage, we are limited to speculation over the actual causes of the recent extreme sea-ice variability. Given the role that Antarctic sea-ice plays in supporting the rich SO ecosystem (Chapter 9), and in mitigating the worst effects of anthropogenic climate change (Chapter 4), the need to understand this complex and highly coupled atmosphere–ice–ocean system and its recent extreme changes continues to be a pressing issue.

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7

THE ANTARCTIC ICE SHEET AND SEA LEVEL

Contemporary Changes and Future Projections

Benjamin K. Galton-Fenzi, Helen A. Fricker, Jeremy N. Bassis, Anna J. Crawford, Natalya Gomez and Christian Schoof

7.1 Introduction

The Antarctic Ice Sheet (AIS) is the largest body of ice on Earth, located in the Southern Hemisphere over the geographic South Pole. Formed over hundreds of thousands of years through the gradual buildup of snow today the AIS has an average thickness of 2.2 km and covers an area of almost 14 million km^2, about 2.75% of the Earth's surface. In total, the AIS contains 30 million km^3 of ice and represents about 62% of the world's total freshwater (Shiklomanov, 1993). If the AIS were to completely melt, global sea levels would rise by about 58 m (Figure 7.1). The AIS is roughly separated by the trans-Antarctic Mountains into two regions, with distinct drainage basins that route grounded ice to the ocean, where each drainage basin has its own ice shelf or ice shelves that are fed by glaciers and ice streams (Figure 7.1). The largest region is the East Antarctic Ice Sheet (EAIS) which covers more than two-thirds of the continent area and contains 52 m of Sea Level Equivalent (SLE). The West Antarctic Ice Sheet (WAIS) has 5.3 m SLE, and the Antarctic Peninsula region has just 0.7 m SLE (Figure 7.1).

The AIS gains mass primarily by snow deposition, and currently loses mass primarily by basal melting and iceberg calving, and to a smaller extent surface melting and sublimation. The buildup of ice in the interior and loss of ice near the coasts causes the ice surface to slope towards its margins. This drives ice flow, which redistributes mass from higher elevation inland to lower elevation at its margins, and regulates how much the AIS contributes to the global sea level. The AIS is surrounded by ice shelves, which form where grounded ice flows into the ocean at the grounding zone and cover nearly 40% of the Antarctic continental shelf seas. The grounding zone is a transition zone between fully grounded and freely floating ice that is typically a few kilometres wide. Ice shelves can impede the flow of

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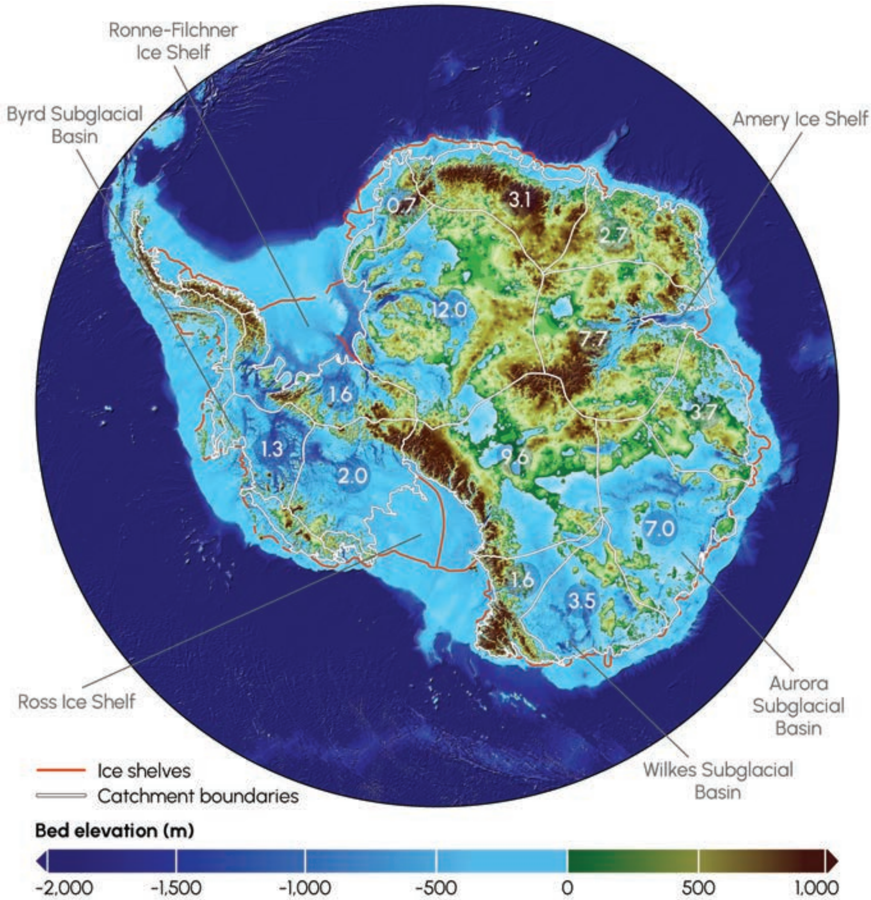

FIGURE 7.1 Antarctic bedrock topography from BedMachine (Morlighem et al., 2020), with drainage basins (Rignot et al., 2011), and estimated global mean sea level potential from each basin, in metres (Tinto et al., 2019).

ice discharge from the grounded ice upstream. When an ice shelf drags against bedrock walls or seafloor highs, resistive forces are transmitted upstream, which reduces driving stress and therefore the flow of ice across the grounding line. This effect is known as "buttressing" (Thomas and Bentley, 1978), and loss or reduction of buttressing can increase discharge of grounded ice to the ocean, causing Sea Level Rise (SLR; e.g. Scambos et al., 2004; Gudmundsson et al., 2019). Ice shelves also influence the surrounding ocean with the freshwater generated through their basal melting being a significant source of cold and freshwater into the Southern Ocean.

In this chapter, we explore several important questions, including:

- *How will Antarctica contribute to sea level in the coming decades to centuries?*
- *What processes and regions should be the focus of future scientific research?*
- *What key processes and regions control uncertainty in projections of future behaviour of the AIS?*

We begin with a review of the processes and feedback that control ice-sheet evolution before providing an overview of the present state and trends of the AIS. We then discuss the deep uncertainty in ice-sheet behaviour, and how this is implicated in future projections of change to the ice sheet. We conclude by examining how sea level will change at a regional scale due to mass loss from the AIS. The locations of the places referred to in the text are shown in Figure 0.1.

7.2 Factors Governing Ice-Sheet Evolution

Understanding the primary controls on the ice sheet and ice shelves and the processes that act to alter them is key to understanding their evolution (Figure 7.2). There are several key interrelated factors (geographical, internal and external) that determine the structure and rheology of ice shelves, and control their mass balance processes. Geographical factors, such as topography (Figure 7.1) and the

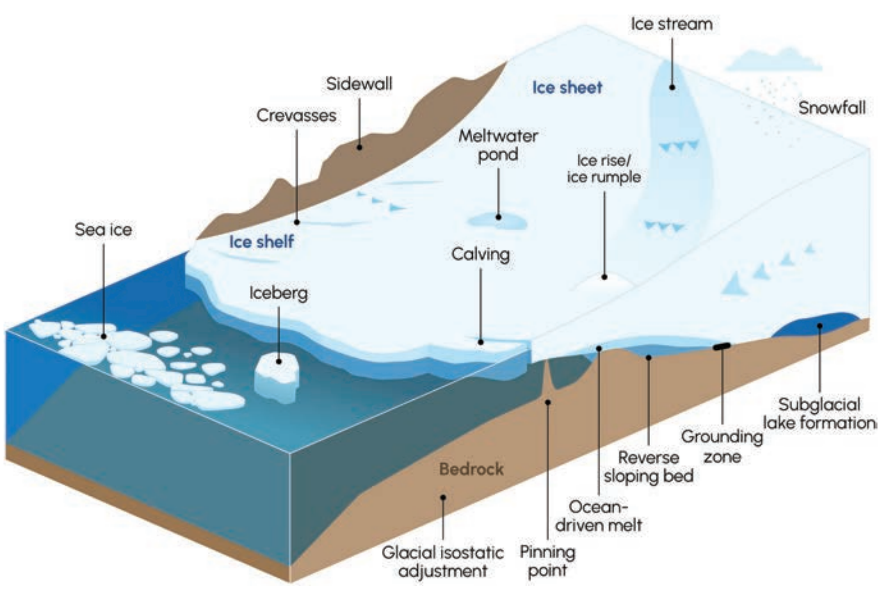

FIGURE 7.2 Schematic of processes affecting the evolution of the Antarctic Ice Sheet.

underlying conditions, set the ice thickness at the grounding line, the ice draft and the sub-ice cavity shape, including the basal and sidewall contact points. Internal factors, such as ice temperature, history and age of ice, ice type (firn vs meteoric vs marine ice), impurities and the degree of damage (crevasses and rifts), set the ice rheology. External factors are the atmospheric and oceanographic settings, which affect both surface and basal processes. These processes also interact with each other, and act on multiple spatial and temporal scales; the response of the ice sheet to future climate states will depend on these interactions and feedbacks. In this section, we describe the main controls on ice-sheet evolution.

7.2.1 Processes

Ice rheology: Ice flow is controlled by its rheology, i.e., how deformable the ice is, which depends on the ice temperature, the orientation of the ice crystals (its fabric) and the presence of impurities in the ice, and by how readily it can fracture. Several factors determine the relative magnitude of the stress applied during ice flow that can feedback on the ice rheology. At the low stresses generated by the small surface slopes in the interior of the ice sheet, ice flows as a polycrystalline solid (Cuffey and Paterson, 2010; Treverrow et al., 2012). Over shorter time scales (measurable in hours) ice can behave as an elastic solid, and the ability to release stored elastic energy can be important for the brittle fracture of ice. The deformation rate (or strain rate) of ice in tertiary creep is sensitive to deviatoric stress (roughly speaking, the shear force per unit area in the ice; Glen, 1955). Consequently, ice velocity more than quadruples if ice thickness or surface slope doubles, and bedrock troughs play a large role in channelising ice flow.

The relationship between strain rate and stress is also dependent on temperature, impurities (e.g., air, sediment or salt; however, their influences are poorly known) and the presence of any meltwater when the temperature is close to the melting point (Paterson and Budd, 1982). In general, warmer and wetter ice deforms more easily. In turn, the temperature of the ice is controlled in part by flow, as faster flow leads to more internal deformation that dissipates more heat. This leads to potentially self-sustaining feedback in which faster flow warms the ice, causing even faster flow. Feedback of this type allows ice to self-organise into patterns of alternating fast- and slow-flowing features (Hindmarsh, 2009), potentially leading to the formation of "ice streams" (Joughin et al., 1999).

Sliding: The high velocities of ice streams, around 100–1000 m per year (e.g., Joughin et al., 1999), are caused by rapid sliding at the interface between ice and bed, or rapid deformation within the underlying bed near that interface (Alley et al., 1986). Both of these processes require ice temperatures at the melting point to provide the highly-pressurised liquid water needed to permit rapid basal motion (see also Bentley et al., 1998, Tulaczyk et al., 2000). Basal ice is often at a temperature close to the pressure melting point (−0.87°C under 1 km of ice), or the ice may even be undergoing active melting. Melting is due to a combination of geothermal heating and frictional heat generated as the ice slides over bedrock and sediments (e.g., Tulaczyk et al., 2000). Subglacial meltwater lubricates the ice to enable sliding, which has resulted in the formation of ice streams (Hughes et al., 1977; Bentley, 1987). An additional self-sustaining feedback can contribute to ice stream formation: warming of the bed due to dissipation of heat by incipient sliding (Hindmarsh, 2009; Mantelli et al., 2019), and the production of meltwater by frictional dissipation once the melting point is reached (e.g. Kyrke-Smith et al., 2014, Schoof and Mantelli, 2021), although the details remain poorly understood (e.g. Mantelli and Schoof, 2019).

Ice shelf buttressing: The degree of buttressing of an ice shelf is set by (a) the lateral drag exerted on it by the sidewalls, where concentrated deformation leads to the formation of distinctive shear margins, and (b) the lateral and basal drag due to "pinning points" (localised topographic highs on the seafloor that come in contact with the base of the ice shelf (Figure 7.2; Goldberg et al., 2009). The amount of drag resulting from contact with sidewalls and pinning points or scales with contact area and friction. Long narrow ice shelves, such as Amery Ice Shelf, have negligible extensional stresses at the grounding line due to the large lateral shear from the margins (Pegler, 2016). However, for most ice shelves, stability is controlled primarily by compressive stresses between key pinning points (Still, 2018).

Although complete ice-shelf removal has the strongest effect on buttressing (Sun et al., 2020), it can also be reduced through ice-shelf thinning (Haseloff and Sergienko, 2018; Gudmundsson et al., 2019), with melting near the grounding zone and sidewalls having a large influence on buttressing and ice flow (Gagliardini et al, 2010; Reese et al, 2015). Buttressing can be lost gradually as the ice is thinned through ocean-driven melting (Gudmundsson et al., 2019). More rapid reductions in buttressing can also occur if overall thinning or retreat via calving is sufficient to weaken or lose the compressive arch, or to cause loss of contact with a pinning point (Still et al., 2019). Buttressing is also impacted by the weakening of shear margins through the formation of cracks (Macgregor et al., 2012) or melting (Alley et al., 2019).

Snowfall and surface melting: Snowfall is the only way the surface of the AIS gains mass. Surface mass budget (SMB) is the net result of mass gain, including precipitation (solid and liquid), and mass loss, including surface melting, evaporation, sublimation and runoff (Lenaerts et al., 2019), and is influenced by atmospheric interactions, such as drifting snow and katabatic winds (Mottram et al., 2021). Snowfall that falls on the AIS compacts under its own weight into firn, which can be O (10–100) m thick. Surface melting is a less significant mass loss process for the AIS than for Greenland, and while it has been linked to ice-shelf collapse on the Antarctic Peninsula (Scambos et al., 2004), it has not yet been detected to occur in large volumes upstream of the grounding zones anywhere in Antarctica. However, 65,000 surface lakes were tallied in 2017, of which 60% were on ice shelves, many located just downstream of grounding zones (Stokes et al., 2019).

Surface melting on Antarctic ice shelves has been projected to double by 2050 (Trusel et al., 2015), which has implications for ice-shelf stability (Warner et al., 2021; Kingslake et al., 2017; Bell et al., 2018). In the longer term, surface meltwater could spread upstream of the grounding lines and ultimately may reach the bed through moulins, leading to faster ice-sheet flow and influencing sub-ice-shelf ocean dynamics, a process that presently occurs in Greenland (Trusel et al., 2018). Recent studies suggest it is not just melt but also the ratio of melt over accumulation that matters to the SMB (Donat-Magnin et al., 2021).

Basal melting and refreezing: Conditions that drive the ocean circulation in the ice-shelf cavity and govern basal melt rates are a complex interplay between the shape of the cavity geometry, basal roughness and many types of processes in the ocean and external forcing (Dinniman et al., 2016; Adusumilli et al., 2020; Rosevear et al., 2024). Deeper ice that is in contact with seawater melts faster than shallow ice due to the pressure dependence on the freezing temperature of seawater (McDougall et al., 2014). Typically the deepest parts of an ice shelf are immediately adjacent to the grounded ice. Melting here steepens the surface of the ice flowing into the ice shelf and leads to a stronger reduction in buttressing than melting elsewhere (Gagliardini et al., 2010) and can drive feedback with ice flow leading to the evolution of basal channels (Dow et al., 2018; Section 2.2).

Generally, more melting occurs at depth which both cools and critically also freshens the ocean, forming ice shelf water that is therefore more buoyant and will ascend along the underside of an ice shelf. Basal melting of ice shelves may also be influenced by subglacial meltwater and associated sedimentation processes (Gwyther et al., 2023), and other oceanographic processes (e.g., tides, eddies, open ocean, sea ice and atmosphere processes). For some ice shelves, typically those with the deepest drafts, the rising meltwater can become supercooled – cooler than the local freezing point temperature of seawater – leading to the formation of marine ice. Marine ice is created by the accretion of frazil – small ice crystals that grow in seawater and can accrete to the ice base and directly refreeze to the ice shelf base (Lewis and Perkin, 1986; Galton-Fenzi, 2012). Some ice shelves that fringe EAIS have significant marine ice that is thought to contribute to ice shelf stability (e.g., 9% by volume for Amery Ice Shelf; Fricker et al., 2001) that can potentially arrest the development of rifts (Khazendar et al., 2009).

Rifting and calving: Although ice flows like a viscous fluid over long-time scales, on shorter timescales, it can also act like a brittle solid and fracture to form crevasses, which can extend vertically and horizontally. Once a crevasse has fully extended through the thickness of the ice, a rift forms, and the horizontal growth of such rifts can lead to large iceberg calving events (Benn et al., 2007). The initiation and propagation of crevasses and rifts thus control the calving behaviour of ice shelves; though this is a normal process in ice-shelf mass loss, it also can influence ice-shelf stability (e.g., Hulbe et al., 1998; Walker and Gardner, 2019; Bassis et al., 2024).

Around half of the overall AIS mass loss occurs through iceberg calving (Greene et al., 2022), which is represented by a spectrum of sizes and time scales from the formation of large, tabular regular icebergs that occurs infrequently, to the production of many small and irregular icebergs that occurs more frequently (Bassis et al., 2024). Most iceberg calving is part of a natural cycle that balances episodic retreat of ice-shelf fronts with gradual advance through ice flow. Rifts and crevasses frequently initiate where stresses in the ice are concentrated: along the margins of ice shelves and near pinning points. Although pinning points generally increase buttressing and decrease the flux of grounded ice, interaction with pinning points has been associated with ice-shelf fracture following ice-shelf thinning. Rifts that propagate from these locations can contribute to the loss of buttressing by weakening the ice shelf even before an iceberg fully detaches (De Rydt et al., 2018). Rifts in Antarctic ice shelves can be filled with marine ice – ice that forms from the ocean beneath ice shelves - or a mixture of snow, sea ice and blocks of ice (mélange) that has been hypothesised to provide different amounts of structural integrity (Hulbe et al., 1998; Khazandar et al., 2009). On some ice shelves, refrozen marine ice can heal rifts from below (Holland et al., 2009) leading to reduced fracturing and increased stability (Craw et al., 2023).

7.2.2 Feedbacks and Instabilities

The processes that affect mass balance are interconnected and can involve mutually-reinforcing feedbacks (Figure 7.2). The possibility of switching from mutually-reinforcing to mutually-suppressing feedbacks leads to the presence of "tipping points" in the ice sheet, where instability and dramatic change can be triggered at a critical threshold. For a cold, ocean-terminating ice sheet like the AIS, retreat could be significantly influenced by the self-reinforcing feedback processes known as the marine ice sheet instability (MISI) (Weertman, 1974; Thomas and Bentley, 1978) and the marine ice cliff instability (MICI) (Bassis and Walker, 2012; Crawford et al., 2021; DeConto and Pollard, 2016; Pollard et al., 2015) (Figure 7.3). Both are characterised by the rate of mass loss increasing as the depth to the sea floor at the grounding line increases. This depth will progressively increase if the grounding line retreats across a reverse-sloping bed – also known as a retrograde bed – (Figure 7.3), leading to accelerating mass loss. The creep-flow-related mechanisms underlying MISI are relatively well understood. By contrast, the MICI conjecture relies on thresholds and rates that depend on processes controlling the fracture of ice, which are less well understood.

In ice-sheet models, the flow-geometry coupling can reverse MISI and stabilise the grounding line on a retrograde slope (Gudmundsson et al., 2012). This stabilising effect hinges on there being a sufficiently long and narrow ice shelf with limited mass loss from basal melting. In the absence of calving, a retreat of the grounding line can then occur without a comparable retreat in the position of the calving front (the ice face at a glacier's terminus), leading to a longer shelf with a stronger buttressing effect (Schoof et al., 2017; Haseloff and Sergienko, 2018). Gomez et al. (2010a) suggested isostatic adjustment and changes in the geoid associated with grounding line retreat can further mitigate the onset of MISI, even on retrograde slopes. These nuances show that MISI – when it occurs – is not controlled solely by the local geometry of the ice-sheet bed but involves multiple feedbacks and processes that can mitigate runaway retreat.

MISI: Although initially controversial, it has since been shown that the simplified case of ice flow on a retrograde bed is always unstable (Weertman, 1974; Thomas and Bentley, 1978; Schoof, 2007a) until other factors, such as buttressing and changes in thermal properties, can complicate the potential feedback. This is because flux through the grounding line increases with the deviatoric stress and ice thickness (Schoof, 2007b; Figure 7.3a). In the absence of buttressing, this results in MISI, as stress at the grounding line, then also increases with ice thickness, and therefore (the ice being just afloat) with depth to the sea floor. In practice, ice shelves do exert buttressing and the geometry of the bed varies laterally and

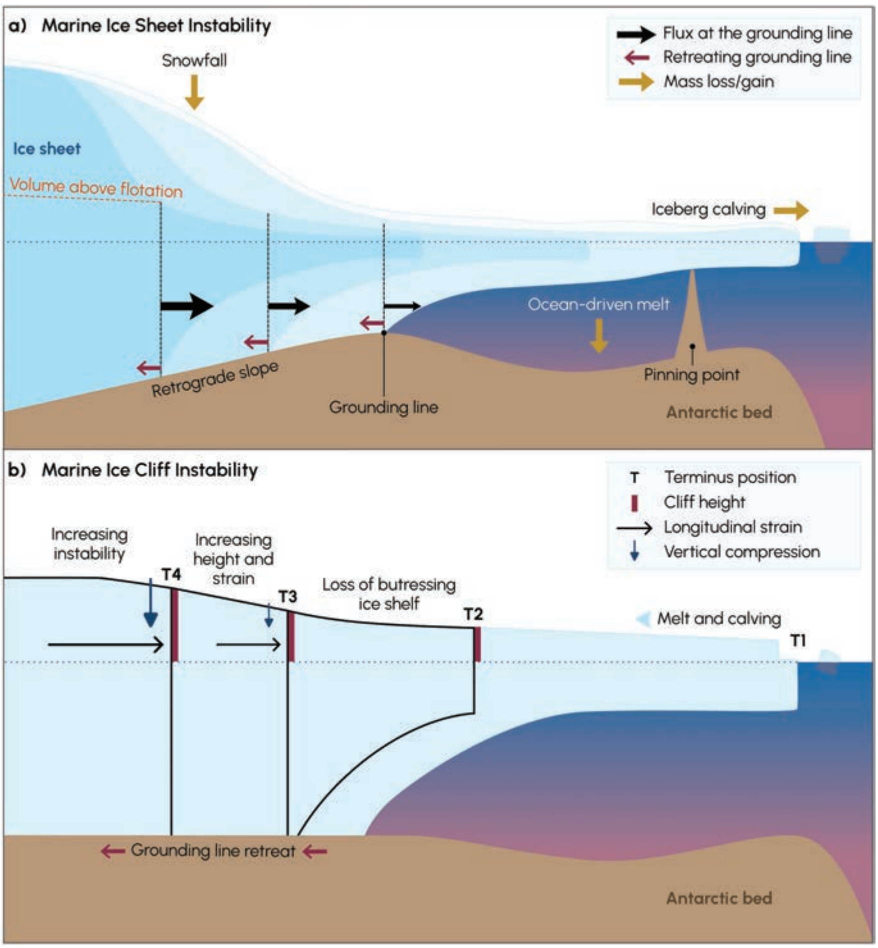

FIGURE 7.3 Feedbacks driving ice sheet evolution: (a) Marine Ice-Sheet Instability (MISI). (b) Marine Ice Cliff Instability (MICI).

temporally, and the strength of buttressing is not simply dictated by external forcing but is coupled to the migration of the grounding zone.

MICI: If a grounded calving face is exposed after the loss of an ice shelf, ice-cliff failure could initiate if the calving face extends past a threshold height above the sea surface (Figure 7.3b). That threshold corresponds to a point at which the calving face is not able to withstand stresses generated by the weight of the ice (Bassis and Walker, 2012). At its simplest, a stress threshold might be expected to cause an irreversible cascade of calving events once initiated: as soon one piece of ice has been removed by calving, thicker ice upstream is exposed producing a sequence of ever taller cliffs that results in a runaway collapse, known as MICI. Calving does not need to be instantaneous and a self-sustaining retreat will only occur if newly-exposed calving faces are not drawn below the threshold height by dynamic thinning caused by horizontal stretching (Bassis et al., 2021; Crawford et al., 2021).

There are no direct observations of MICI; therefore, there is large uncertainty in the threshold cliff height after which ice-cliff failure will initiate, as well as the ensuing retreat rates. Existing attempts to quantify ice-cliff retreat rates for the purpose of predicting future ice-sheet evolution have either used parameterisations based on limited data (DeConto and Pollard, 2016) or calibration against synthetic results (Crawford et al., 2021). Recent studies are beginning to compare rates of retreat of calving cliffs that are close to the theoretical limit (e.g., Needell and Holschuh, 2023) to provide more empirical constraints on cliff failure.

7.3 Present State and Trends

Satellite estimates show that the AIS has been losing mass since the 1990s, and this loss is accelerating with time (Otosaka et al., 2023). Mass loss has been dominated by changes in WAIS (see Figure 7.4) (Smith et al., 2020). The latest study (Otosaka et al., 2023) has shown that for the period 1992–2020, ice loss from WAIS and the Antarctic Peninsula were 82±9 Giga-tonnes per year (Gt yr^{-1}) and 13±5 Gt yr^{-1}, while EAIS had a small gain of 3±15 Gt yr^{-1}. All recent studies agree on the trend of ice loss from WAIS and the Antarctic Peninsula, and on the rate of loss having increased since around 2006 (Rignot et al., 2019; Otosaka et al., 2023).

West Antarctica: Most research on processes that contribute to AIS mass loss has focused on WAIS (e.g., Rignot et al., 2014; Joughin et al., 2014). Satellite laser altimetry over grounded and floating ice (Smith et al., 2020) has shown that between 2003 and 2019, WAIS lost 76 ±49 Gt y^{-1} of floating ice and −169 ± 10 Gt^{-1} of grounded ice (7.5 mm SLE). Basins that drain into the Amundsen Sea Embayment (Figure 7.1) have experienced dramatic changes (Figure 7.4a); here, the ice shelves are in contact with warm ocean waters and have experienced enhanced melting and thinning (Adusumilli et al., 2020; Smith et al., 2020) and grounding line retreat (Khazendar et al., 2015). Ice-shelf thinning and grounding-line retreat have led to reduced buttressing on the upstream grounded ice, and the dynamic thinning has spread inland (Gudmundsson et al., 2019; Section 2). Accelerated ice flows of glaciers, such as Thwaites and Pine Island into the ocean (Smith et al., 2020; Otasaka et al., 2022), are contributing to SLR. Because this drainage basin is vulnerable to MISI (Figures 7.1 and 7.3a), the onset of instability remains difficult to confidently determine at this time. Changes in processes have been triggered by this thinning: e.g., the floating portion of Pine Island Glacier has transitioned from a previously quasi-stable cycle of advance and retreat at its calving front to a calving regime characterised by more frequent detachment of tabular icebergs and calving front retreat (Jeong et al., 2016). Similarly, portions of the Thwaites Glacier ice tongue underwent an abrupt change from a previously intact ice shelf into fragmented remnants (Miles et al., 2020). Although ocean forcing has been implicated in these transitions, the changes to the Pine Island and Thwaites ice shelves were not predicted by models used to simulate ice-sheet and ice-shelf processes. This highlights that the processes leading to shelf fracture and disintegration remain poorly understood and must be a priority for future research.

East Antarctica: EAIS is estimated to be close to balance or even slightly positive in its mass change (Martín-Español et al., 2016; Smith et al., 2020; Otosaka et al., 2023). This is because mass losses from the ocean-driven melt are compensated by increased snowfall over its large area (Smith et al., 2020; Otosaka et al., 2023; Figure 7.4a). Rignot et al. (2019) estimated an EAIS SLR contribution of 4.4 ± 0.9 mm from 1979–2009. Satellite laser altimetry for 2003–2019 (Smith et al., 2020) has shown EAIS gained a total of 90 ± 21 Gt y^{-1} of floating ice and 106 ±29 of grounded ice (−4.0 mm SLE). There are regional differences in behaviour within EAIS. Increases in snowfall are concentrated in Dronning Maud Land (Velicogna et al., 2014; Smith et al., 2020), while multiple studies measure ongoing mass loss from Wilkes Land since the mid-2000s (Velicogna et al., 2014; Smith et al., 2020). Wilkes Land is susceptible to MISI and glaciers there are showing signs of change (Li and Dawson et al., 2023).

Since satellite observations began there have been major calving events from several ice shelves, but the record is short compared to the calving cycles. However, for ice shelves with a more rapid calving cycle, recent observations point to the influence of ocean and atmospheric forcing on increasing calving rates, as is evident from retreat and terminus change at Pine Island (Bradley et al., 2022) and Thwaites Glacier (Seroussi et al., 2017). The influence of increasing atmospheric temperatures on calving, ice-shelf stability and retreat has been particularly dramatic in the Antarctic Peninsula, e.g., the 2002 collapse of the Larsen B Ice Shelf. Historic radar altimetry (which extends only to 72°S) suggests that changes in the Antarctic Peninsula began before 1992 (Fricker and Padman, 2012).

Over the past five years (2019–2023), ICESat-2 observations have detected a change in the pattern and rate of snow accumulation (Fricker et al., 2020; Adusumilli et al., 2023). WAIS gained accumulation via several short-period extreme events, driven by moisture-laden atmospheric rivers, contributing 41% of the increases in height in 2019 (Adusumilli et al., 2023). The subsequent years, especially 2020 and

2021, displayed ongoing ice losses around the margins and gains in the interior. In 2022, there was a large amount of snow accumulation and the surface mass balance anomaly reached +325 Gt (net mass gain of 290 Gt; Adusumilli et al., 2023). Spatial patterns indicated increased elevations, particularly over EAIS in Wilkes Land.

7.4 Future Projections and Deep Uncertainty

Projections of the future SLR contribution from the AIS are highly uncertain (Figure 7.5). Projections up to 2100 show that the AIS represents a relatively small fraction of SLR contribution, in the absence of rapid ice-sheet collapse, but from 2100 to 2300 has the potential to be the dominant source of SLR. Recent projections for ice-sheet evolution indicate a potential sharp acceleration in SLR towards the end of this century (Edwards et al., 2021), with high-end scenarios indicating the small possibility that global SLR could exceed 1.5 m by 2100 (Figure 7.5). This led to a new high-end risk scenario being introduced with IPCC (2021) stating that a global rise "approaching 2 m by 2100 and 5 m by 2150 under a high greenhouse gas emissions scenario cannot be ruled out due to deep uncertainty in ice-sheet processes". Deep uncertainty occurs when experts and/or decision makers do not know or cannot agree upon the system model relating actions to consequences or the prior probabilities on key parameters of the system model (Lempert and Collins, 2007). The large range of SLR projections confuses many efforts for coastal adaptation on century time scales (Dietz et al., 2022; Hirschfeld et al., 2023).

Large uncertainties in projections come from deficiencies in: (i) understanding of processes and feedbacks that influence ice-sheet evolution (Seroussi et al., 2024); (ii) knowledge of ice-sheet and near-ocean geometry and conditions (e.g., how the shape and evolution of the bed and presence of subglacial water and ocean melting can influence flow); and (iii) future climate model projections used as input to these simulations of ice-sheet evolution (Li et al., 2023).

Future ice-sheet behaviour subject to tipping points depends sensitively on initial conditions and climate forcing. This means that, even when the processes that control thresholds and tipping points are well understood, small changes in climate forcing or initial conditions can lead to large differences in projected SLR. This was demonstrated by Robel et al. (2019) for MISI, where simulations using the same ice-sheet model subject to intrinsic variability in climate forcing resulted in a large distribution of grounding line retreat rates and associated SLR. For processes like ice shelf collapse and MICI, which depend on poorly-quantified thresholds, the uncertainty in outcomes is even larger as small changes in under-observed parameters can lead to diverging results. Therefore, SLR projections are often treated probabilistically with the various thresholds and instabilities leading to substantial probabilities for more extreme outcomes in a "negatively skewed" distribution (Robel et al., 2019), providing what are actually unknown-likelihood, but potentially high-impact events (Figure 7.5).

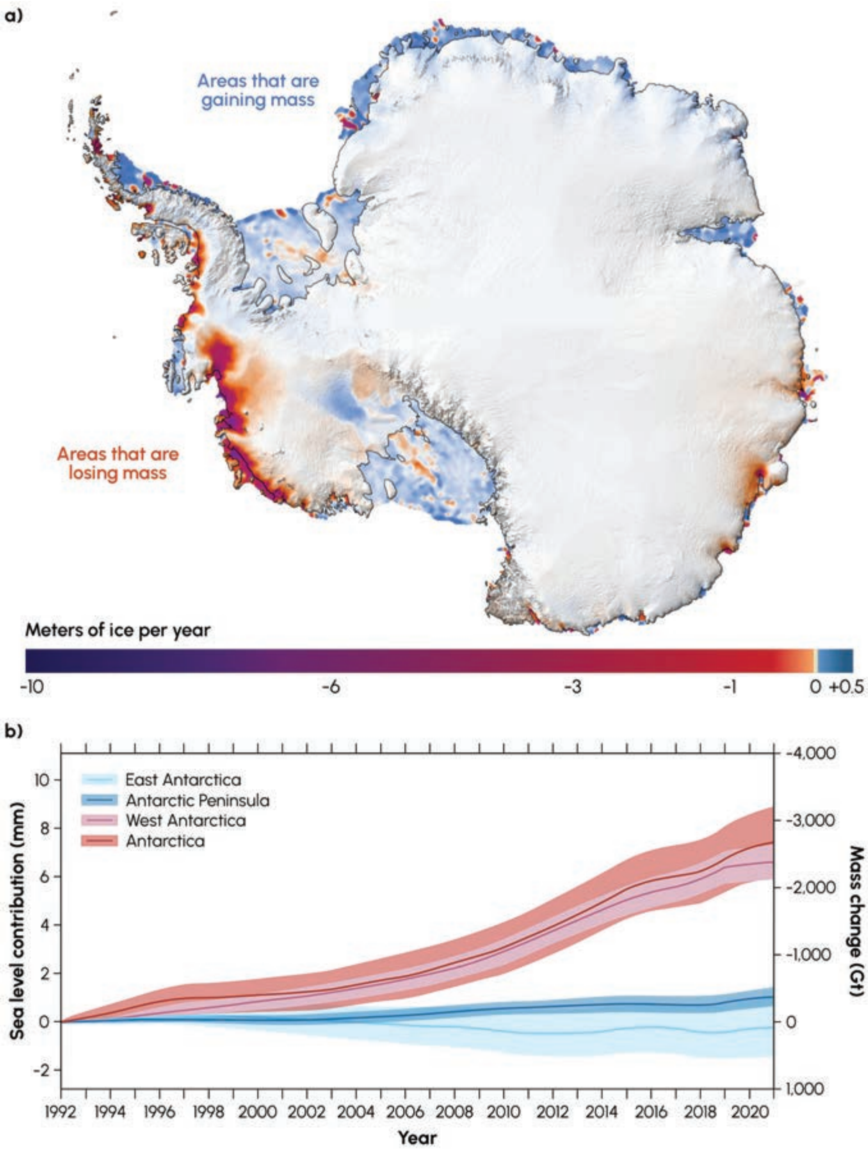

FIGURE 7.4 Antarctic mass loss: (a) Ice-sheet thinning for grounded and floating ice between 2003 and 2019 estimated by differencing elevations from NASA's Ice, Cloud and land Elevation Satellite (ICESat) and ICESat-2 laser altimeters (Smith et al., 2020). (b) Cumulative Antarctic mass loss compiled from 24 separate studies by the IMBIE team (adapted from Otosaka et al., 2023); shading represents the associated uncertainties.

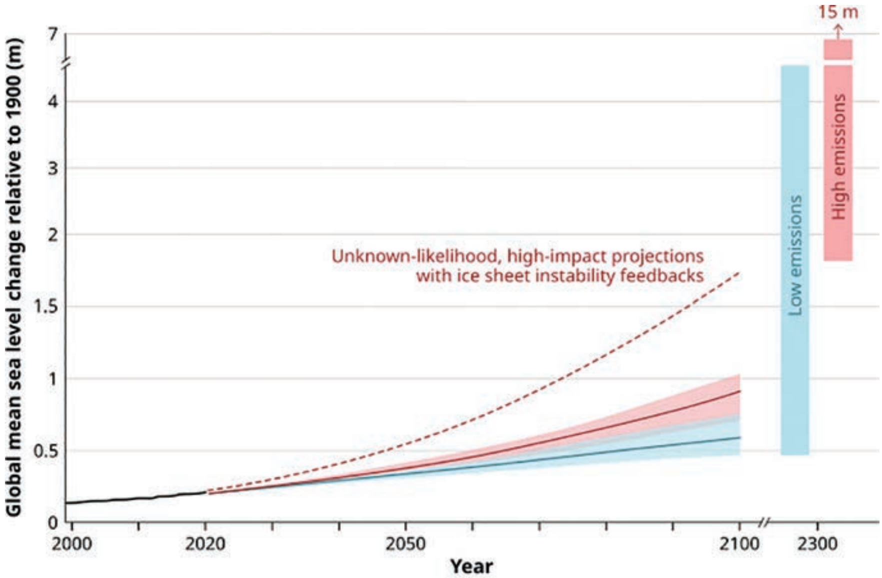

FIGURE 7.5 Global SLR IPCC AR6 climate projections from 1990 to 2100 and 2300 (metres relative to 1950; adapted from IPCC, 2021).

Many processes occur in complex areas on spatial scales that are too small to be resolved by current satellite data; for example, observing ice-shelf rifts (Walker et al., 2021), grounding zones (Freer et al., 2023) and melt rates in basal channels require high-resolution observations of ice-shelf height (Alley et al., 2016) and flexure (Rignot et al., 2024). One of the largest uncertainties remains the open question of how to appropriately represent the various processes through which calving occurs above and below the height threshold at which ice-cliff failure might initiate (MICI).

There is significant variability in atmospheric and oceanic climate forcing used to drive models, and potential feedbacks remain poorly quantified (e.g., Hanna et al., 2024). For instance, since ice shelves play a buttressing role, ice-sheet behaviour is prone to intrinsic variability driven by ocean melting of the ice shelves that can produce a pseudo-steady state, advancing or retreating behaviour (e.g., Gwyther et al., 2018; McCormack et al, 2021). The ISMIP6 project came to little consensus on the role of emission scenarios in driving ice-sheet change because increased snowfall, particularly over EAIS, can significantly offset some of the expected increase in discharge. There is similar significant uncertainty in ocean forcing (Seroussi et al., 2020). The influence of these external processes on the projected uncertainties seems to be as important as the influences of approximations in model physics and simulated ice evolution (Seroussi et al., 2024).

7.5 Regional Sea Level Changes

AIS melting is expected to dominate global mean SLR in the coming centuries, but site-specific sea level changes are very heterogeneous, and can be dominated by regional and local processes such as subsidence and coastal erosion in some areas. Local SLR (in addition to other factors such as changing storm frequency and strength) in turn can intensify the impact of extreme sea level and flooding events (IPCC, 2021). Here, we focus on characterising the spatially variable sea level changes associated with AIS evolution. Changes in the distribution of ice cover of the AIS cause spatially variable sea level changes that are often much higher or lower than global average sea level. The global pattern of sea level changes associated with AIS loss is primarily due to the effects of gravity, changes in Earth rotation and viscoelastic deformation of the solid Earth, often referred to as "gravitational, rotational and deformational (GRD) effects" (Farrell et al., 1976; Mitrovica et al., 2011; see Figure 7.6). The addition of meltwater to the oceans can also contribute to more localised spatial variability in sea level changes (Golledge et al., 2019).

Ice mass loss on timescales of years to centuries leads to a local drawdown of the geoid – the gravitational equipotential corresponding to the sea surface – and uplift of the solid Earth, which, combined, lead to a relative sea level fall within roughly 2000 km of the region of ice loss (Woodward, 1888; Mitrovica et al., 2011). This sea level fall can be an order of magnitude or more larger than the global average SLR. Gravitational effects also lead to a greater than average rise at greater distances from the melting ice sheet. Crustal uplift beneath oceanic areas freed of marine-based ice expels water out of the vicinity of the melting ice sheet further amplifying far-field SLR, an effect termed "water expulsion" (Gomez et al., 2010b). Water loading of the global oceans also deforms the solid Earth in the far-field, adding to the spatial variability of the sea level change associated with the ice loss. Finally, the ice mass loss drives a shift in the Earth's rotation axis towards the region of ice loss, and this, in turn, redistributes water in the oceans, acting to decrease relative sea level in quadrants of the Earth's surface that approach the rotation axis and increase relative sea level in the other quadrants (Milne and Mitrovica, 1998).

Solid Earth deformation due to surface ice and ocean loading changes is in general viscoelastic, with a largely elastic response on short, years to centuries, timescales and viscous flow of the Earth mantle towards isostatic equilibrium on longer timescales (Peltier, 1974). Viscous deformation depends on the thickness of the lithosphere and viscosity of the Earth's mantle. Viscosities are variable across relatively short spatial scales and much lower in some areas (e.g., Barletta et al., 2018; Lloyd et al., 2020), leading to viscous uplift in response to ice unloading occurring on timescales of years to decades in some areas rather than the more typical millennial and longer timescales. Substantial uncertainty remains in the structure and associated response of the solid Earth in Antarctica, with implications for ice mass loss estimates (IPCC, 2021).

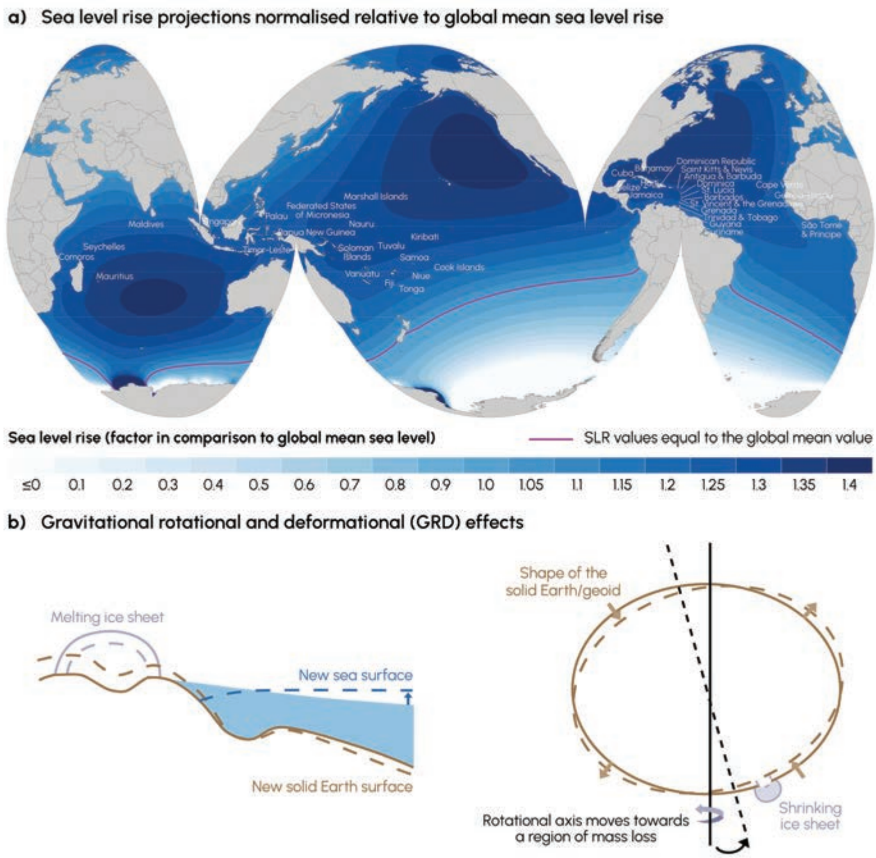

FIGURE 7.6 Antarctic Ice Sheet deglaciation impacts on regional sea level changes: (a) Pattern of sea level factor at 2100 under RCP4.5 – the mid-level future emissions estimates (adapted from Sadai et al., 2022): e.g., a factor of 1.2 indicates SLR 1.2 times the global mean. (b) Schematics of the physical effects causing the spatial variability in sea level changes in (a): left – gravitational effects on the sea surface and deformation of the solid Earth; right – the effects of Earth rotational changes (adapted from Whitehouse et al., 2018).

Global sea level patterns due to recent and future ice loss: Sea level changes due to ice loss from the AIS combine with the effects of Greenland ice loss, resulting in up to about 30% greater than average SLR in mid- to low-latitude regions by the end of the century (Golledge et al., 2019; Figure 7.5). However, much greater local SLR amplification can occur in some areas on decadal timescales when more localised patterns of ice cover changes drive constructive interference between GRD effects (Roffman et al., 2023). The global pattern of SLR away from the ice sheets is significantly more sensitive to the geometry of Antarctic ice loss than to that of Greenland ice, loss due to its location on the rotation axis. Uncertainty in projections of AIS ice loss (Seroussiet al., 2020) in turn leads to uncertainty about the projected regional patterns of sea level changes (Roffman et al., 2023).

WAIS ice loss produces SLR peaks greater than 30% higher than the global average along North American coastlines and in the Indian Ocean (e.g., Gomez et al., 2010b; see Figure 7.6a), while SLR peaks due to EAIS melting are shifted relative to the WAIS case to the North Pacific and South Atlantic Oceans, mainly due to rotational effects. Some coastal areas will experience larger impacts of SLR at lower levels of warming than other areas, highlighting the climate injustice implications of global mean temperature targets (Sadai et al., 2022). For example, Small Island Nations, which are already experiencing SLR impacts, are expected to see a greater than average rise associated with AIS loss in the future regardless of the ice-sheet model projection and level of future warming (Roffman et al., 2023; see Figure 7.6). Multiple decades of far-field sea level measurements are required to detect the contribution of recent ice loss to global sea level above natural variability and ocean dynamic effects (Kopp et al., 2010), and have only recently begun to be detected in sea surface altimetry and tide gauge records (e.g., Moreira et al., 2021). Earlier detection is possible in the near-field of the ice sheets where the signal is larger and detection will improve with longer and more near-field records as ice mass loss accelerates.

7.6 Summary and Future Research Directions

The AIS is the largest body of ice on Earth, and it will continue to have a profound influence on sea level and Earth's climate. We have provided a review of how we expect Antarctica to contribute to sea level in the coming decades and beyond, what we understand from trends in behaviour since the 1990s and what we currently think to be the most important processes and behaviours that should continue to be the focus of future scientific research to best constrain uncertainty in projections of the future behaviour of the AIS.

We set out to explore the questions posed in the introduction and here, in summary, we present the following approaches that we have identified as necessary to ensure progress:

Processes: Integration between new observations, simulations and laboratory experiments is needed to evaluate and constrain models of key processes, including buttressing, sliding dynamics, subglacial water behaviour, basal melting and freezing of ice shelves, ice rheology and the influences of impurities, the formation and evolution of features such as ice shelf rifts and basal channels, surface mass budget processes, solid Earth processes and processes that govern the far-field impacts of SLR. Work is also needed to understand processes driving both temporal variability (Hanna et al., 2024), and AIS tipping-points, including those that cause shelf fracture and disintegration. (Winkelmann et al., 2023)

Modelling: Planning requires credible projections based on physical ice-sheet and climate models. The most significant uncertainties in projections of ice-sheet evolution are associated with climate forcing and the fidelity of present ice-sheet models to represent key physical processes. Uncertainty estimates can only be reasonably achieved by examining large suites of possible future outcomes. Continued development of state-of-the-art models is therefore critical to combine advanced process understanding with observations. This will lead to useful simulations that can guide and aid interpretation of measurements and provide future projections with substantially constrained uncertainties.

Observations: Targeted high-resolution observations of the AIS and surrounding oceans, sea ice, atmosphere (climate) and solid Earth are critical to refine the understanding of processes for modelling, fill in gaps in maps of bedrock and ice-sheet shape and assess the state of the ice sheet and cavities beneath the ice shelves. Long-term monitoring of key locations of the AIS and bedrock and sea level in the Southern Ocean are critical to provide enhanced confidence in present-day trends and associated contributing processes. The EAIS, specifically the Wilkes and Aurora subglacial basins, must be a focus of future activity.

Coordinated science: Concerted system-scale approaches are needed to link together the different components that are often studied individually, given the critical feedbacks and interconnected processes we have identified. Sustained and coordinated effort is key to make the best use of resourcing with multi-national collaborations to pool expensive logistics resources. The pathway to improvements needs complementary use of field, satellite, laboratory and simulations, which is presently underutilised (Cook et al., 2022, Gwyther, 2018). The approach can be used to prioritise research focus needed to make progress on constraining future contributions from the AIS to SLR within the next decade.

The substantial uncertainty in the AIS contribution to future SLR, especially the deep uncertainty under high-end warming, presents a delicate challenge for coastal planning efforts (Kopp et al., 2023; van de Wal, 2022), which use widely varying SLR projections in adaptation decisions (Hirschfeld et al., 2023). For many applications, the deep uncertainty is dominated by the social environment when decision makers and stakeholders do not agree on the likelihood and magnitude of future scenarios. Scientific uncertainties are typically much smaller than the uncertainties associated with socio-economics and appropriate decision making frameworks. Constraining the deep uncertainty to enable adaptive planning and decision making must therefore involve all stakeholders – funding bodies, scientists, planners and policy-makers – to ensure ongoing advances in ice sheet and sea level science are made for society to be able to adapt and react to future change.

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8

POLLUTION IN ANTARCTICA

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8.1 Introduction

Antarctica's isolation from lower latitude pollutants due to natural barriers like circumpolar atmospheric and oceanic currents means it is undoubtedly less polluted than other parts of the world (Barker and Thomas, 2004). However, less than 32% of its landmass is considered 'pristine' and non-impacted by human activities (Pertierra et al., 2017; Leihy et al., 2020). In this chapter, we examine well-known currently well-regulated pollutants primarily associated with tourism, research stations, growing risks of oil, fuel spills from accidents within Antarctica and increased shipping in the Southern Ocean (SO) (e.g., Ruoppolo et al., 2013; Brooks et al., 2024; Stark, 2022). We then assess some 'novel' pollutants associated with mid-late 20th century anthropogenic activities outside of Antarctica whose impacts and ecological threats are not yet fully established (e.g., Bergami et al., 2023).

8.2 Pollutants Sources Associated with Human Activities in Antarctica

Despite the vast size of Antarctica (14,000,000 km^2) (Figure 0.1), ice-free ground where most terrestrial biodiversity is found is scarce and represents less than 0.3% of the continent's area (c. 42,000 km^2) (Terauds et al., 2012). Most Antarctic terrestrial biological communities, bird colonies and seal haul-out sites are found on ice-free ground within 5 km of the coast, an area of c. 6,000 km^2 (Hull and Bergstrom, 2006). Human activities have been focussed largely within this small area since people arrived ~ 200 years ago.

Antarctic nearshore environments contain some of the richest marine habitats yet are extremely vulnerable to human impacts from shipping and tourism (Aronson et al., 2011). At locations subject to prolonged human presence and/or the activities

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of multiple national Antarctic programmes, cumulative impacts can be substantial, resulting in environmental degradation (Braun et al., 2014). The main impacts from habitat destruction, disturbance of wildlife, introduction of non-native species and pollution (Tin et al., 2009), and expansion of the human footprint across ice-free regions of Antarctica puts human needs in direct competition with those of nature (Pertierra et al., 2017; Brooks et al., 2019; Hawes et al., 2023). We examine the key pollution sources in Antarctica (tourism, research stations, sewage, wastewater, fuel spills, and local emissions) in the following section.

Tourism: Antarctic tourism facilitated over 104,000 visitors, predominantly to the Antarctic Peninsula, during the 2022/2023 season (International Association of Antarctica Tour Operators, 2023). The construction of permanent infrastructure to support this is not currently permitted, yet some national Antarctic programmes have permanent or semi-permanent infrastructure for tourism and non-governmental activities (Netherlands, 2023). Antarctic tourism numbers have dramatically rebounded following the COVID-19 pandemic, and ship-based tour operators continue to identify new sites for tourist visits while diversifying the range of activities available (Bender et al., 2016; Hughes and Convey, 2020) (Figure 8.1).

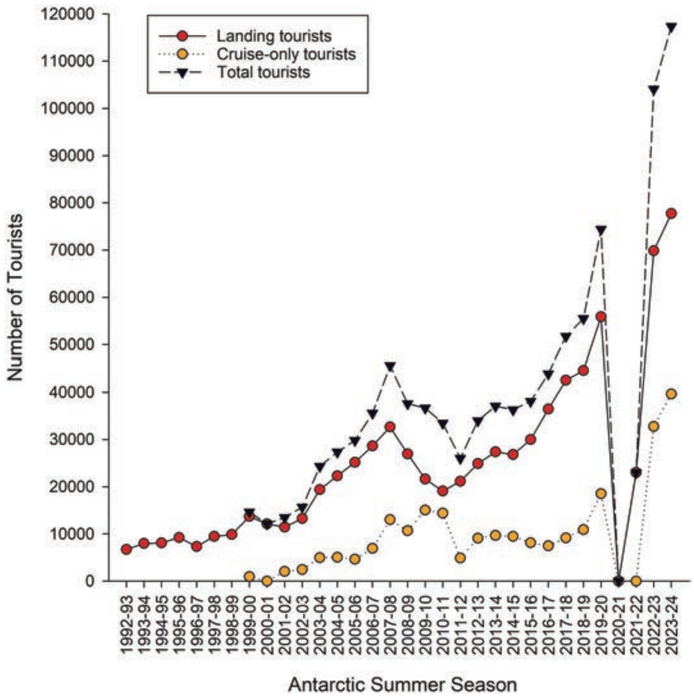

FIGURE 8.1 Number of tourists visiting the Antarctic Treaty area facilitated by members of the International Association of Antarctica Tour Operators (IAATO, 2023). Data for 2023/2024 are estimated by IAATO. Fewer tourist numbers during the 2020/2021 and 2021/2022 seasons were due to the COVID-19 pandemic.

Research stations: Research stations have negative impacts on local geomorphology, biological communities, and aesthetic and wilderness values (Klein et al, 2008; Kennicutt et al., 2010; Brooks et al., 2019; Palmer et al., 2022). Since the International Geophysical Year (1957/58), scientific activities have expanded significantly. There are now 75 research stations with an estimated 5000 national operator staff working in Antarctica annually (COMNAP, 2022, Chu et al., 2019). Substantial, but often uncharacterised, levels of impact have resulted from the construction and operation of facilities (including research stations, ports, and airstrips) by governmental Antarctic programmes, and seasonal and deep field camps (COMNAP, 2017).

Nations with a longer presence on the continent are currently investing heavily in redeveloping their Antarctic infrastructure (e.g., Argentina, Australia, New Zealand, UK, USA), or constructing additional stations in new locations (e.g., China). Stations provide nations with a mechanism to demonstrate substantial scientific research activity and participate in the governance of the Antarctic Treaty area by becoming a Consultative Party to the Antarctic Treaty Consultative Meeting (Gray and Hughes, 2016; Karatekin et al., 2023). Abandoned stations and historical waste dumps generated before the 1998 Environmental Protection to the Antarctic Treaty Protocol, which prohibits the dumping of waste, are found across the continent, creating substantial local pollution and associated impacts (e.g., Fryirs et al., 2013; Stark et al., 2023). Notably, several abandoned stations built on ice shelves between 1950 and 1990, such as the UK Halley I–IV on the Brunt Ice Shelf and the South African SANAE I–III stations on the Fimbul Ice Shelf, have calved into the ocean (Aronson et al., 2011).

There are many examples of quarrying and construction activities destroying breeding habitats for birds and terrestrial biological communities (Ewing et al., 1989; Wilson et al, 1990; Hughes et al., 2016; 2023), although some attempts have been made at relocating vegetation (Câmara et al., 2021). Trampling and compression of Antarctic soils by pedestrian traffic and vehicle movement affect soil properties and biodiversity, with visual impacts remaining decades after the original event (Tejedo et al., 2014). Human visits and wildlife disturbance from aircraft and, more recently, remotely operated vehicles, can lead to reduced reproductive success and displacement of biota (Chwedorzewska and Korczak, 2010; Coetzee and Chown, 2016; Mustafa et al., 2018).

Sewage and wastewater: Release of sewage and wastewater is the only waste disposal into the Antarctic environment permitted under the Protocol (Annex III), and only when environmental conditions provide initial dilutions and rapid dispersal. Treatment is not mandatory, but at a minimum, sewage maceration should be undertaken at research stations with more than 30 personnel. For stations located on floating ice shelves or inland areas of permanent ice, disposal of sewage and wastewater in deep ice pits is allowed as it is the only practicable option.

Sewage disposal standards date back to 1991 when the Protocol was agreed but are now considered inadequate (ATS, 1998 a, b). Treatment of sewage is increasingly undertaken at research stations, but more than 50% lack sewage treatment and large seasonal fluxes in sewage are prevalent (Gröndahl et al., 2009; COMNAP, 2022). Some research stations, such as the Belgian Princess Elizabeth base in Dronning Maud Land, East Antarctica (Figure 0.1), have invested heavily in sustainable microbial treatment and greywater recycling facilities that can recycle up to 75% of wastewater (Alvarez et al., 2015). Elsewhere, outdated practices have led to the release of sewage into local terrestrial and freshwater environments, or microbial and chemical contamination of streams and lakes (Peter et al., 2009; Tort et al., 2017; Hawes et al., 2023).

Sewage release has many negative consequences for the nearshore marine environment several kilometres from the outfall (Stark et al., 2016). Released chemicals include metals and metalloids (hereafter referred to collectively as metals), persistent organic pollutants (POPs), surfactants, and nutrients that change aquatic community structures (Wild et al., 2015; Webb et al., 2020; Szopińska et al., 2021; Stark et al., 2023). Effective sewage treatment prevents ongoing impacts (Conlan et al., 2010), but remedial treatment is needed to remove persistent pharmaceutical chemicals (e.g., analgesics, anti-inflammatories, antibiotics, estrogens, fungicides, preservatives, UV filters, and surfactants) whose negative impacts are well-established (Emnet et al., 2015; Perfetti-Bolaño et al., 2022). Wastewater disposal into the Antarctic environment releases sewage-derived microbial strains, which are used as markers for tracing the extent of sewage contamination, but have negative impacts on local biota by, for example, spreading antimicrobial-resistant genes (Hughes, 2003; Power et al., 2016; Hernández, et al., 2019; Hwengwere et al., 2022; Corti et al., 2023).

Fuel spills: The most significant large-scale fuel spill in Antarctic marine or terrestrial environments was the sinking of the Argentine naval supply vessel, *Bahai Paraiso* in 1989, at Arthur Harbour, near Palmer Station, Anvers Island (Figure 0.1), which resulted in the loss of ~600,000 litres of fuel and subsequent impacts upon bird and marine invertebrate populations (Kennicutt et al., 1992). Many areas around stations have been subject to chronic fuel and other POPs contamination, primarily due to oil spills and poor infrastructure maintenance, but also as a result of the long-distance transport of industrial by-products (Peter et al., 2009; Golubev, 2021).

Away from stations, leaking oil drums left in (abandoned) station dumps have resulted in substantial quantities of contaminated ground with one estimate suggesting between 1 and 10,000,000 m^3 of contaminated soil being present in Antarctica (Snape et al., 2001). For example, lead and zinc in soil in the immediate vicinity of Marambio Station, Seymour Island, Antarctic Peninsula (Figure 0.1) exceeded baseline values by up to five times (Chaparro et al., 2007). Fuel spills can have long-term impacts on soil properties (i.e., moisture, hydrophobicity, soil temperature) and biological communities including microbial activity (Aislabie et al., 2004; Hughes et al., 2007; Vázquez et al., 2017). More positively, some indigenous microorganisms have proven capable of degrading hydrocarbons, including polyaromatic hydrocarbons (PAHs), which has resulted in attempts to remediate contaminated soils *in situ* at some Antarctic locations (McWatters et al., 2016).

Local atmospheric emissions: Atmospheric pollution is an almost inevitable result of fossil fuel combustion to power research stations, ships, aircraft, and overland vehicles. Local levels of atmospheric pollution are generally low compared to other areas of the planet (e.g., nitrogen oxides; Helmig et al., 2020; Marina-Montes et al., 2020), and many emissions originate outside of Antarctica (Wolff, 1992; Leal et al., 2008). Recent examination of snow in the vicinity of research stations and coastal tourist sites found black carbon from fossil fuel combustion to be above background levels measured elsewhere on the continent (Khan et al, 2019; Cordero et al., 2022). This is of particular concern as it can darken the snow, which lowers its albedo and increases melt rates (Cereceda-Balic et al., 2020).

8.3 Novel Pollutants

Many of the pollutants that end up in or around Antarctica and sub-Antarctic Islands have been dispersed globally by atmospheric (Bargagli et al., 2008; Li et al., 2020; Aves et al., 2022), oceanic (Jiskra et al., 2021; Cunningham et al., 2020, 2022), and migration (Wild et al., 2022) processes.

The most common airborne and gaseous pollutants hazardous to health are particulate matter with diameters less than or between 2.5 ($PM_{2.5}$) and 10 (PM_{10}) microns, black and elemental carbon, nitrogen oxides, ozone, sulphur dioxide, POPs, volatile organic compounds, PAHs, per- and polyfluoroalkyl substances, and carbon monoxide associated with industrial, agricultural, and automotive industries (WHO, 2021). Even though the Northern Hemisphere is thought to have a much lower hydroxyl-radical pollution self-cleaning capacity, some of these pollutants have similar concentrations in the Southern Hemisphere to the Arctic (Patra et al., 2014). POPs have been extensively studied in Antarctica since the 1960s, and their negative impact on human, wildlife, and ecosystem health is well-established and regulated by the Stockholm Convention (Goerke al., 2004; Cabrerizo et al., 2013; Marrone et al., 2021; Alfaro Garcia et al., 2022; Garnett et al., 2022; Corsolini et al., 2022; Kuepper et al., 2022). Recent reviews of POPs in Antarctica include: ImPACT Action Group (2021); Cordero et al. (2022); da Silva et al. (2023); Luarte et al. (2023); Kessenich et al. (2023).

Pollution levels in Antarctica can also be assessed by comparison with baseline (pre-industrial) levels at pristine sites (Angulo, 1996) and by using natural archives such as ice cores, lake/marine sediments, and peatland records (Li et al., 2020). For example, evidence of anthropogenic greenhouse gas emissions, including carbon dioxide and black carbon from incomplete combustion of biomass dating back centuries, are preserved in Antarctic ice cores and have been linked to large-scale forest clearance, and changes in settlement patterns and land use on surrounding continents (e.g., McConnell et al., 2021; Thomas et al., 2023; King et al., 2024). Most pollutants have substantially lower concentrations in Antarctica and the SO

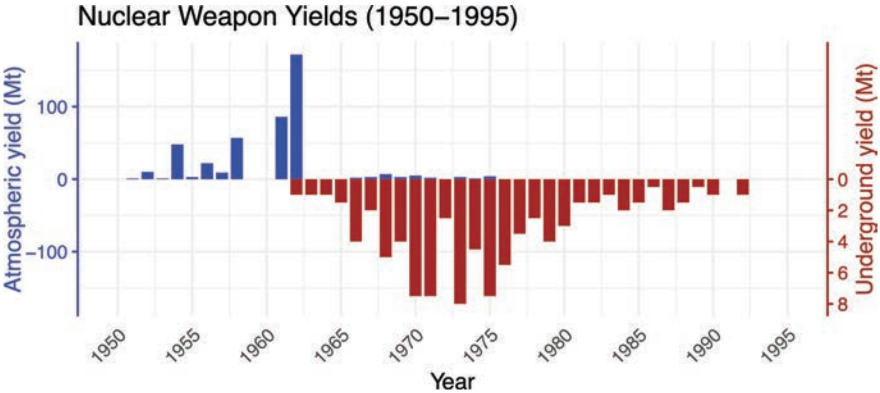

FIGURE 8.2 The shift from atmospheric to underground testing following the ratification of the Partial Test Bay Treaty (PTBT) in 1963 (see Prăvălie, 2014). The Threshold Test Ban Treaty in 1974 banned underground tests greater than 150 kilotons. The Comprehensive Test Ban Treaty banning all nuclear test explosions was adopted in 1996 by the United Nations but has not been ratified by all countries (Giovannini, 2021).

than in populated areas of the Northern Hemisphere due to their remoteness, low population density, and comparative lack of landmass (Bargagli et al., 2008).

In the following section, we highlight some novel (far-travelled) pollutants, such as anthropogenic radionuclides, metals and plastics, that have been found extensively across Antarctica and the SO but remain largely unregulated.

Anthropogenic radionuclides: Perhaps the most dramatic example of a globally dispersed pollutant is radioactive fallout from atmospheric nuclear weapons testing (Figure 8.2). Comparatively little is known about the distribution of anthropogenic radionuclides from atmospheric fallout across the Southern Hemisphere, principally because there are only a few landmasses in the SO, concentrations of these radionuclides are low, and, until recently, analytically challenging to measure (Child et al., 2008, 2013; Arienzo et al., 2016). While the concentrations and impacts of radionuclide pollution are much lower, they can bioaccumulate through the food chain, and, unlike other pollutants, remain radioactive for centuries to millennia (Saunders and Meredith, 2023).

Atmospheric nuclear weapons testing injected anthropogenic radionuclides, principally Radium-226 (^{226}Ra), Caesium-137 (^{137}Cs), and Strontium-90 (^{90}Sr), but also Americium-241 (^{241}Am), Plutonium-239 and -240 (^{239}Pu,^{240}Pu), Uranium-236 (^{236}U), and Iodine-131 (^{131}I) into the stratosphere, which were mixed latitudinally by atmospheric circulation processes, and distributed globally as fallout (United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000). Of the 2053 nuclear weapons tests conducted between 1945 and 2006, more than a quarter (530) were tested in the atmosphere before the Partial Test Ban Treaty, which restricted atmospheric testing, came into effect in 1963 (Figure 8.2).

Approximately 83% of the 530 Mt total explosive yield detonated between 1951 and 1992 (440 Mt) was due to atmospheric tests conducted between 1951 and 1980, with the Former USSR and the USA the largest contributors, followed by China, France, and the UK (Prăvălie, 2014) (Figure 8.2). Although only 10% of tests were conducted in the Southern Hemisphere, between 1945 and 1980 the fallout inventory in the Southern Hemisphere was approximately one-third of that in the Northern Hemisphere (UNSCEAR, 2000; Hancock et al., 2011).

Anthropogenic radionuclides, such as ^{137}Cs, ^{241}Am, and ^{239}Pu, have been found in soil, lichens, mosses, cryoconite, peat deposits, ice core records and lake/marine sediments (Li et al., 2017; Szufa et al., 2018). Caesium-137 fallout, which peaked in 1963, is widely used as a chronological marker in lake, marine, and peat records globally (Foucher et al., 2021) (Figure 8.3). While the concentration of ^{137}Cs in records from the Southern Hemisphere high latitudes is often very low or below detection limits (Li et al., 2017) (Figure 8.3), the timing of the ^{137}Cs peak varies between 1963 and 1965, likely due to the time taken for atmospheric mixing between the Northern and Southern Hemispheres (Foucher et al., 2021).

Similarly, plutonium isotope peaks linked to radioactive fallout have increasingly been found in ice cores from the Arctic and Antarctica (Arienzo et al., 2016) (Figure 8.3). Recent analytical improvements mean it is possible to measure fallout radionuclides, such as ^{239}Pu at peta-m concentrations. This advance led to the recent discovery of ^{239}Pu and ^{240}Pu in soils, peat deposits and lake sediments from sub-Antarctic Islands and Tasmania, significantly widening their known spatial coverage (Harrison et al., 2021).

The relatively large amounts of ^{239}Pu, ^{240}Pu, and ^{236}U released during atmospheric weapons testing and different isotopic signatures used by different countries in weapons manufacturing can be used to track changing fallout patterns (Figure 8.3c) (Hotchkis et al., 2000). The impact of USA testing in the Southern Hemisphere and Former USSR testing in the Arctic up to 1970, and the post-1970 shift to Chinese testing in the Northern Hemisphere and French testing in the Southern Hemisphere is shown in Figure 8.3. Consequently, ^{240}Pu/^{239}Pu atom ratios found in some records from sub-Antarctic latitudes are towards the lower end of the global range of 0.16–0.19 (Kelley et al., 1999) and have been attributed to tropospheric fallout from French nuclear tests in the Pacific during the 1960s and 1970s (Chamizo et al., 2011; Kelley et al., 1999).

Metals: The occurrence and accumulation of metals have been recorded in Antarctica in soils, marine sediments, and biota (Bargagli, 2008; Koppel et al., 2021). Research stations are the main source of locally derived metal contaminants, originating from waste dumps and contaminated sites but also local geology (Regoli et al., 2005; Aronson et al., 2011; Padeiro et al., 2016; Webb et al., 2020). Impact assessments highlight arsenic, cadmium, copper, lead, mercury, and zinc as elements of most concern (Tin et al., 2009).

Some metals are emitted by industrial processes in gaseous form, while others become associated with fine particles or remain as by-products and confined to

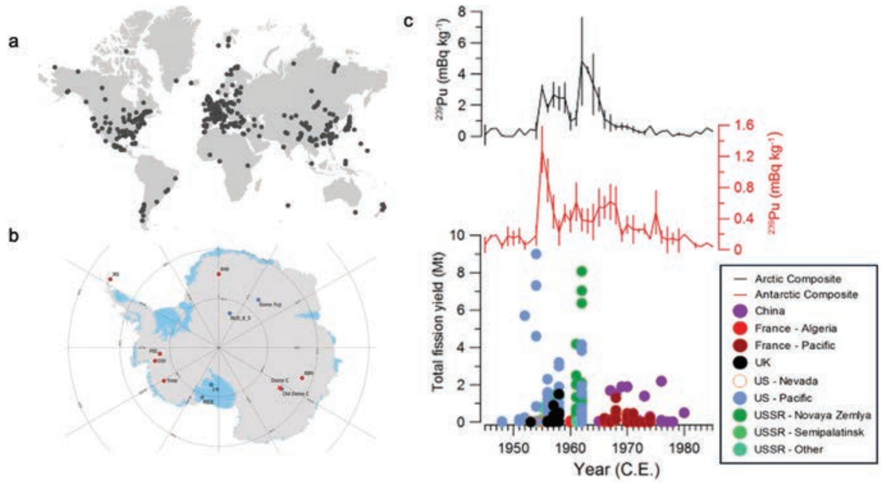

FIGURE 8.3 (a) Global distribution of sediment core records containing ^{137}Cs, highlighting the comparative lack of records from the Southern Ocean region (modified from Foucher et al., 2021; https://creativecommons.org/licenses/by/4.0/). Caesium-137 peaks have also been found in lake sediments from the Falkland Islands, Signy Island (Appleby et al., 1995), and South Africa (Rose et al., 2021) (not shown on maps). (b) Location of ice cores and snow pits where ^{239}Pu has been detected in Antarctica (from Severi et al., 2023). (c) Arctic (black line) and Antarctic (red line) composite ice core records of ^{239}Pu activities (with standard error bars) and a summary of total fission yields by country and testing locations (reprinted from Arienzo et al., 2016, copyright 2023 American Chemical Society).

industrial facilities (Hopke et al., 2020). Metals in gaseous form, such as mercury, can travel long distances within the atmosphere before being deposited in remote areas like Antarctica (Bargagli, 2008; Whiteside and Herndon, 2022; Marina-Montes et al., 2020). Consequently, elevated concentrations of metals above natural background levels have been observed in the atmosphere, snow, soil, and aquatic ecosystems of Antarctica far from research stations (e.g., Szopinska et al., 2021).

Although only 10% of the world's population resides in the Southern Hemisphere, major economies, such as Argentina, Australia, Brazil, Chile and South Africa, are significant consumers of coal and key producers in the mining sector (Figure 8.4). These nations have high industrial emissions rates, and their geographical proximity to Antarctica facilitates the transport of metals to the region (EIA, 2023; World Mining Data, 2023).

Studies from Australia have shown that pollutants from mining activities travel long distances, with the potential to affect the SO and sub-Antarctic Islands, such

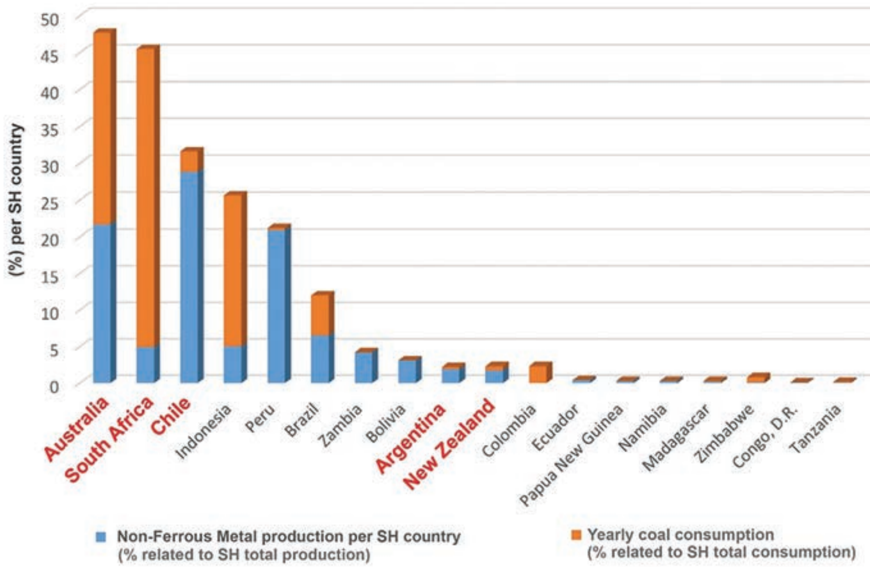

FIGURE 8.4 Antarctic gateway states, including Argentina, Australia, Chile, New Zealand, and South Africa (bold), are among the top consumers of coal and leading non-ferrous metal producers in the Southern Hemisphere (World Mining Data, 2023).

as Macquarie Island (Figure 0.1) (Schneider et al., 2019). Both Southern South America and Africa also contribute significant amounts of metals to the sub-Antarctic (Li et al., 2020) and Antarctic (Planchon et al., 2002; Tuohy et al., 2015; Schwanck et al., 2017, 2022; Fan et al., 2021; Liu et al., 2021), and most regulatory frameworks governing pollution in these countries are weaker (Sinclair and Schneider, 2019; Fisher et al., 2023).

Long-term studies examining archives of metal deposition indicate an increase in metals across Antarctica from pre-industrial to post-industrial periods. Ice core records from Dome A and the Antarctica Peninsula (Figure 0.1) indicated that enrichment factors of antimony, arsenic, cadmium, copper, and lead were significantly larger than 10, which is predominantly due to mining production and burning of coal in Australia and South America (Liu et al., 2021). Other ice core studies show consistent, albeit varying, increases in metals since the end of 19th century, including lead (Schwanck et al., 2022; McConnell et al., 2014; Hong et al., 1998; Vallelonga et al., 2002; 2004; Görlach and Boutron, 1992), cadmium (Hong et al., 1998; Schwanck et al., 2022), copper (Hong et al., 1998; Vallelonga et al., 2004), and arsenic (Schwanck et al., 2016). A compilation of available peat and lake sediment records, alongside independent estimates of global mercury emissions, has shown that mercury deposition in the Southern Hemisphere has been enriched fourfold since the C15th (Li et al., 2020).

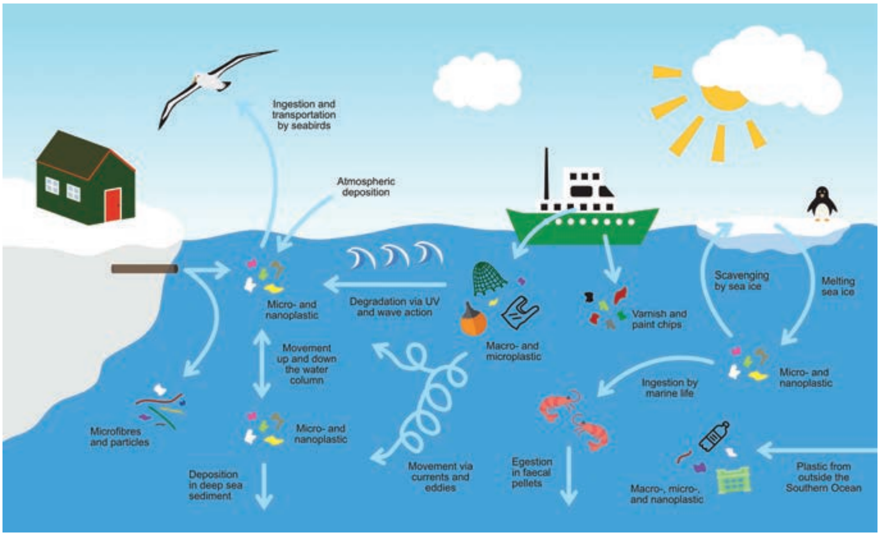

FIGURE 8.5 Summary of major sources and contamination pathways of plastics on and around Antarctica.

Plastics: Plastic pollution in the SO is being increasingly recorded, with sources, including local pollution from fishing vessels and research stations, and debris transported on currents from elsewhere (Waller et al., 2017). Plastic release from research stations is likely to be minimal on a continental scale, but substantial amounts of plastic debris, including fishing equipment, have been found on beaches at various locations in the Antarctic region (Munari et al., 2017; Reed et al., 2018; Waluda et al., 2020) (Figure 8.5).

Depending upon the properties of the plastic, it may float or sink, thereby accessing different benthic and pelagic habitats, and can persist in the environment for decades or longer (Cuningham et al., 2020; Rowland et al., 2021a; Rota et al., 2022). Large plastic items can be hazardous to wildlife, through ingestion or entanglement, and may act as vectors for the transfer of non-native species (Arnould and Croxall, 1995; Barnes, 2002). Microplastics (particles or fibres <5 mm) can be released in wastewater, produced, for example, by clothes washing, but a more substantial source may be the degradation of larger fragments of marine plastic debris due to exposure to solar UV radiation, chemicals, biological processes, and physical damage. The impact of microplastics on Antarctic biodiversity remains unknown but may include reduced feeding efficiency and reproductive success in Antarctic krill (*Euphausia superba*) (Dawson et al., 2018; Rowlands et al., 2021b). Plastic pollution has the potential to substantially impact key Antarctic species, particularly when combined with other environmental and anthropogenic stressors (Rowlands et al., 2021b). Horton and Barnes (2020) also highlighted that Antarctic organisms face a number of stressors in the SO and that the impact of plastics should not be studied in isolation.

While the definition of nanoplastics is still debated, the consensus is that any plastic particle smaller than 1 μm is classified as a nanoplastic (Hartmann et al., 2019). Like microplastics, nanoplastics are largely formed via the breakdown of larger plastic items, although some primary sources exist (Piccardo et al., 2020). Initially, in terms of transport mechanisms and impact, nanoplastics were thought of as an extension of microplastics (Moore, 2008), however recent studies have shown that the behaviour of these particles is often quite different (Gigault et al., 2018; Gigault et al., 2021; Pradel et al., 2023).

The study of nanoplastics in the environment is a relatively new field (Ter Halle et al., 2017; Piccardo et al., 2020), presenting unique size-related analytical challenges. Although the sources, transport, ecological impacts, and fates are not well understood, much work has been undertaken in the related field of hydrocarbon and POP 'chemical' pollutants since the 1960s in Antarctica (de Silva et al., 2023 for review). To date, there has only been one study of nanoplastics in Antarctica, reporting values of 37.7–60.0 ng mL^{-1} in a sea ice core (Materić et al., 2022). Reports of microplastic concentrations in the SO are more numerous, with values ranging from zero (Kuklinski et al., 2019) to over 500 particles L^{-1} (Garza et al., 2023).

Despite a lack of data, nanoplastics are predicted to be as pervasive as microplastics (Alimi et al., 2018), and perhaps more so, since nanoplastics can be transported extremely long distances in the atmosphere (Materić et al., 2022). Moreover, the length of time it takes for the long-range transport of oceanic plastic pollution to reach Antarctica gives ample time for fragmentation into smaller size fractions (Obbard, 2018) and there are many potential sources of plastic pollution within the SO (Rowlands et al., 2021b). As an emerging field, there is limited literature on the impact of nanoplastic on Antarctic organisms (Alice et al., 2021), but nano-sized polystyrene spheres have been found to affect the immune response, swimming abilities, and gut epithelium of Antarctic marine organisms (Bergami et al., 2019; Bergami et al., 2020; Bergami et al., 2022). Rowlands et al. (2021a) observed impaired embryonic development of Antarctic krill when exposed to polystyrene nanoplastic particles. Furthermore, the impacts of nanoplastic on krill (Rowlands et al., 2021a) and the sub-Antarctic pteropod *Limacina retroversa* (Manno et al., 2022) were found to be worse when subjected to a multi-stressor environment.

Policies related to plastic pollution have been implemented within the SO; the International Convention for the Prevention of Pollution from Ships (MARPOL, Annex V) legislates against the disposal of plastic overboard (International Maritime Organisation (IMO), 1988), while the Antarctic Treaty prohibits the release of macroplastic waste into the Antarctic environment (Secretariat to the Antarctic Treaty, 1998). While guidelines are in place for plastic use on research stations (SCAR, 2024) and in the tourism industry (IAATO, 2019, 2020), no regulations exist. Collaborative governance under the Antarctic Treaty presents an opportunity to put research findings into policy and create international action (Secretariat to the Antarctic Treaty, 1961).

8.4 Impact of Climate Change on Pollution in Antarctica

Shifts in atmospheric circulation and global warming may further enhance the transport and deposition of pollutants to Antarctica (Convey et al., 2009; Turner et al., 2014). For example, increases in pollutant deposition in Antarctic ice cores have been attributed to increased cyclonic activity associated with more poleward-focused and stronger Southern Hemisphere westerly winds (Schwanck et al., 2022). This is driving sea ice poleward, increasing the advection of warm and moisture-laden air across the Antarctic and sub-Antarctic (Marshall et al., 2017; Oliva et al., 2017; Heredia Barion et al., 2023), likely enabling increased wet deposition of contaminants. Melting ice sheets and thawing permafrost and snowpack can also release previously trapped substances into surrounding environments (Pérez-Rodríguez et al., 2019).

8.5 Summary

- Since the International Geophysical Year, scientific activities and tourism in Antarctica have expanded significantly, with more than ~100,000 people visiting the continent annually. Most visits are made to the Antarctic Peninsula where numerous pollution-related incidents have been reported.
- Research stations are the main source of locally derived contamination and human activities have led to substantial increases in the long-range deposition of pollutants to Antarctic and sub-Antarctic regions.
- Greater focus on the evaluation of impacts that largely unregulated pollutants could have on Antarctic and SO environments and ecosystem health in the future is required.
- Future changes in climate, including increased rainfall and melting ice from Antarctica, will lead to increased concentrations of pollutants across Antarctic terrestrial and marine environments.
- Global distribution mechanisms may have a more substantial influence, requiring local versus global sources to be established and disentangled prior to the establishment of effective policy and mitigation strategies.

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9

ECOSYSTEM RESILIENCE, FISHERIES AND CONSERVATION IN THE SOUTHERN OCEAN

Status of Knowledge, Prognoses and Challenges

Andrew J. Constable

9.1 Introduction

Antarctic ecosystems have been integral to our awakening that the Earth System, as a life support system, needs safeguarding. From unfettered exploitation to sustainable utilisation, to cultural appreciation, conservation and protection, governance now has an inherent focus on the maintenance of life in Antarctica and the Southern Ocean (Chapter 10). Much of the focus is, unsurprisingly, on Antarctic krill, arguably the most abundant marine metazoan species on Earth (Siegel, 2016), and its predators, attractive to exploitation or easy to access in land-based colonies (Laws, 1984, El-Sayed, 1994, Knox, 2007, Bestley et al., 2020). We have come to learn that this is only half the story. The lower trophic levels in the Southern Ocean – phytoplankton, bacteria, zooplankton and small fish – play a big part in global carbon cycling and buffering climate change (Henley et al., 2020, Cavan et al., 2019).

The 2000s brought greater emphasis to understanding the complexity of Antarctica's marine ecosystems (De Broyer et al., 2014), the role they play in the Earth system (Murphy et al., 2021, Hofmann et al., 2015, Hofmann, 2009, Hofmann et al., 2011) and their sensitivities to a rapidly changing atmosphere (Constable et al., 2023b, Constable et al., 2014). Antarctic fisheries and their effects cannot be isolated and insulated from wider changes in the global marine ecosystems (Trebilco et al., 2020, Constable et al., 2016b) or from their ramifications to the Earth system.

Antarctic marine ecosystems are pivoting because of the declining winter sea ice extent since 2015 (Chapter 6). Until 2015, the total area covered by sea ice in winter had been increasing, contrary to the predictions of declining total winter sea-ice extent from Earth System models. Sadly, the recent sustained declines mean that the Southern Ocean system is now behaving in a manner consistent with projections considered by the Intergovernmental Panel on Climate Change, which do not bode well

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for the Southern Ocean (Holmes et al., 2023). Attention to the resilience of Antarctic marine ecosystems is now urgent and needs a sober assessment on what support these systems will need in the coming years and decades in order to safeguard their longevity, based on science that can pragmatically be achieved.

Resilience is the ability of ecosystems to maintain their attributes, including recover from perturbations (e.g. Reed et al., 2022) – pulse perturbations refer to events over short time scales, such as marine heatwaves, while press perturbations refer to continued pressure on the ecosystem over many years, such as by fisheries. Climate change is a long-term press perturbation at time scales beyond usual considerations of resilience. It is important to frame in these terms because of an expectation for ecosystem recovery once climate is stabilised and restored but also because of the potential for climate change to alter the resilience of ecosystems to shorter-term perturbations. Climate change is altering the mean state of systems as well as changing system variability, including increasing the frequency of extreme events. In Antarctica, changes in variability of events are now being recorded in terms of interannual variation in sea-ice extent and conditions, summer heat waves, phytoplankton productivity and increased severity of weather events. Climate change can amplify some risks from other human perturbations, such as fishing because declining population production can weaken the ability for stocks to recover from long-term harvesting regimes or shocks from heat waves. The combination of multiple and diverse pulse and press perturbations, or greater extremes, can give rise to tipping points, causing failure in populations and long-term, if not permanent, shifts (hysteresis) in ecosystem structure and function (alternative stable states). The risk of complex changes and tipping points in Antarctic ecosystems is believed to be increasing (Constable et al., 2022).

In this chapter, I assess the future of Antarctic marine ecosystems and the attention needed to ensure their long-term resilience in the face of climate change. I examine the nature of these ecosystems (Section 9.2) and the historical impacts of fisheries (Section 9.3). In Section 9.4, I appraise the issues for managing ecosystem risks from Antarctic krill fisheries, the largest fishery in the Southern Ocean. I examine these in detail because the challenges surrounding the orderly development of these fisheries highlight the complexity of achieving precautionary, ecosystem-based management in the Southern Ocean. That complexity is compounded by the recovery of the ecosystem from past over-exploitation and the current and future effects of climate change (Section 9.5). In Section 9.6, I suggest strategies for managing the krill fishery, for achieving broader conservation in the face of climate change, and for considering rational use within the remit of conserving innate ecosystem services. I also argue for urgently building an international, coordinated ecosystem science program to provide a coherent ecological understanding of Southern Ocean marine ecosystems and related services, a program to support regional policy development and management. Lastly, I highlight in Section 9.7 the urgency for re-emphasising a precautionary approach within the Commission for the Conservation of Antarctic Marine Living Resources while the mechanisms are still available to control the Antarctic krill fishery.

9.2 Spatial Ecology of Southern Ocean Ecosystems

Southern Ocean life is organised as interconnected systems (areas), with strong connections to regions outside of the Southern Ocean, including the Arctic (Murphy et al., 2021). Based on the Marine Ecosystem Assessment for the Southern Ocean (MEASO) (Constable et al., 2023b), this section provides an overview of our understanding of the spatial structure of the ecology of the Southern Ocean.

9.2.1 Habitats

The spatial structure of Southern Ocean ecosystems is determined by the topography and geomorphology of the seafloor, the Antarctic Circumpolar Current, the extreme seasonality of light, weather and sea ice, and the diversity of the pool of species able to live in these environments (Constable et al., 2014, Post et al., 2014, Grant et al., 2006) (Chapter 1).

Habitats (the mix of physical conditions) comprise pelagic (water column) and benthic (seafloor) environments. The extent of interaction between them is, in part, determined by bottom topography and depth, with greater coupling in shelf (<800m) habitats through upwelling and deep mixing (Henley et al., 2020, Morley et al., 2020) (Chapter 4). Around Antarctica, sympagic (sea ice) environments, on which many species depend, are a dominant feature (Swadling et al., 2023) (Figure 9.1).

Temperature generally decreases from north to south with rapid change at each of the ACC Fronts (Chapter 4). Temperature influences physiology and metabolism in protists and ectotherms – higher temperatures increase metabolic costs (Johnston et al., 2022, Caccavo et al., 2021, Pinkerton et al., 2021). Many Antarctic species have a narrow range of temperature tolerance, being adapted to the cold temperatures around the Antarctic (De Broyer et al., 2014).

Productivity in the surface environment (euphotic zone) is determined by available light and nutrients with annual net primary production in the Southern Ocean limited by bioavailable iron (Henley et al., 2020). Diatoms, a primary food of Antarctic krill, need high concentrations of iron and silicate (Henley et al., 2020). Productivity is enhanced in shelf areas, around banks, plateaus and seamounts, and at the sea ice edge (Pinkerton et al., 2021).

The Southern Ocean is not uniform in its habitats, zonally or meridionally (De Broyer et al., 2014). MEASO has advanced the previous partitioning to delineate areas small enough to have comparatively homogeneous habitats but large enough to encompass the annual ecologies of populations of most species (Constable et al., 2023b). These areas are then useful to simplify explanations of its ecology, for measuring and predicting change, and for assessing ecosystem-based management. Fifteen MEASO areas are created from five meridional sectors around the Southern Ocean and three zones (Figure 9.2).

The MEASO Zones are delineated by the surface expression of the frontal systems of the ACC (Chapter 4), a similar system to Longhurst (2007). The Antarctic

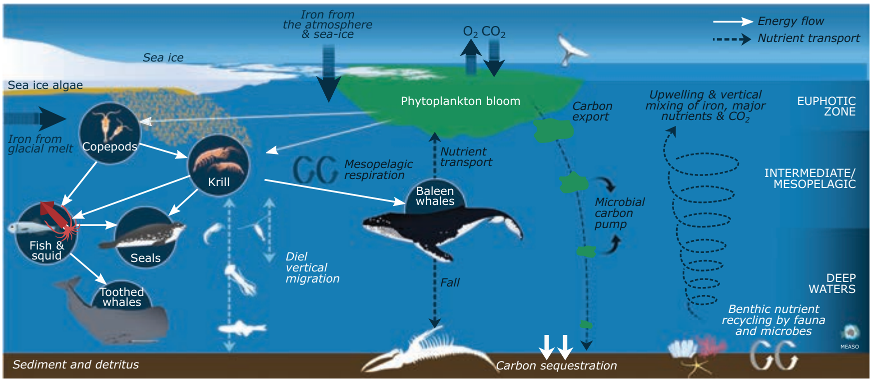

FIGURE 9.1 Biological perspective of the physical environment in the Southern Ocean showing relationships of biota with key habitat variables and processes (after graphical abstract, Henley et al., 2020)

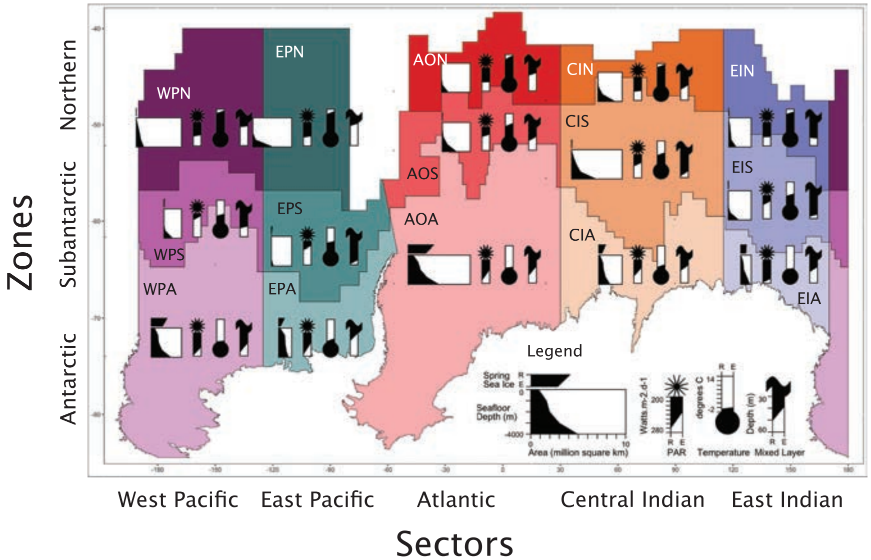

FIGURE 9.2 Summary physical attributes, mean values for austral spring (November–December; a period of peak production), of areas of the Marine Ecosystem Assessment of the Southern Ocean derived, for consistency, from Earth system projections using ACCESS ESM1.5 SSP5–8.5 (business-as-usual) (Ziehn et al., 2020). Derivation of areas from Sectors and Zones is shown (see text for details), including acronyms for each area (as used in Figure 9.5 legend). Size of the box for Seafloor Depth represents size of the MEASO area. For each attribute, differences are between a recent period (R), 1981–2000, and for the end of the century (E), 2081–2100 (see online Supplementary Material). PAR is Photosynthetically Active Radiation.

Zone is dominated by the extreme seasonality in light and sea ice and takes in the Antarctic continental shelf, the east-west coastal current and gyres. It is bounded to the north by the Southern Antarctic Circumpolar Front, which is often considered to be a northern boundary for most of the distribution of Antarctic krill (Cuzin-Roudy et al., 2014). The Subantarctic Zone takes in most of the subantarctic islands, including adjacent shelves, banks and plateaus, while the Northern Zone is a transition area to more temperate waters with a mostly abyssal topography. The Polar Front (Antarctic Convergence) has been used as a defining feature of Antarctic ecosystems (El-Sayed, 1994) but is subsumed into the Subantarctic Zone here because of the activities of marine mammals and birds across the zone (Hindell et al., 2020).

The Antarctic Zone is naturally divided into five sectors because of the gyral influences of the Weddell and Ross Seas (the Atlantic and West Pacific sectors respectively), the south-north projections of the West Antarctic Peninsula (East Pacific Sector), the Macquarie Ridge (East Indian sector) and the Kerguelen Plateau with Prydz Bay (Central Indian sector). These characteristics give rise to the division of the other zones. In this schema, the Scotia Arc is part of the Atlantic sector influenced by both the Weddell gyre and the west-east flow of the ACC through the Drake Passage (see Figure 0.1 for the geography of the region).

Physical attributes of the MEASO areas are illustrated in Figure 9.2, showing the mean projected state of each area for austral spring (November–December), a peak production period in the Southern Ocean (Henley et al., 2020). The mean state of each variable was determined for two periods, 2001–2020 and 2081–2100 using outputs from ACCESS ESM1.5 SSP5–8.5 (business-as-usual scenario) (Ziehn et al., 2020); projections were used in order to provide for consistency in the discussion on climate change (Section 9.5).

9.2.2 Ecosystem Structure & Energy Pathways

Food webs vary according to primary productivity and the types of primary producers, along with drivers of mortality/performance of higher trophic groups not related to the magnitude of production *per se*, such as locations of prey fields for land-based predators (Bestley et al., 2020) and the longevity of winter-breeding ice habitat for emperor penguins (Fretwell, 2024). The types of primary producers dictate which grazers (secondary producers) may be most common and therefore which food chains (energy pathways) are dominant. For example, large diatoms are consumed by Antarctic krill, while smaller protists are consumed by copepods and salps. Each of these is considered as three of the important energy pathways in the food webs of the Southern Ocean (McCormack et al., 2021b, Murphy et al., 2012). The relative importance of these energy pathways in an area will determine whether krill-eating or fish-eating predators dominate (McCormack et al., 2021b, Trebilco et al., 2020) (Figure 9.3), having implications for productivity available to different fisheries and which marine mammals and birds will be prevalent in an area.

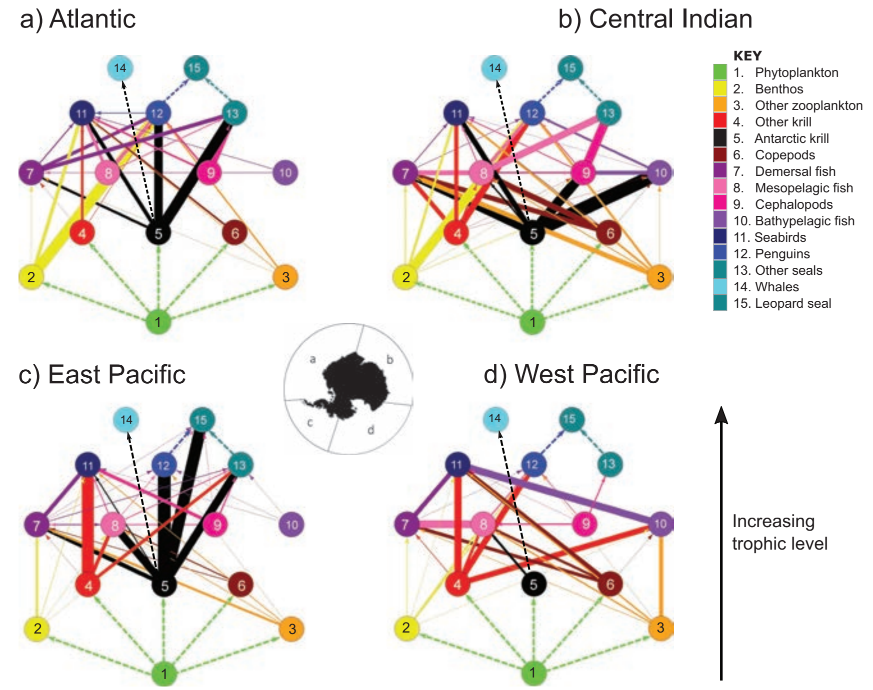

FIGURE 9.3 Broad food web structure in the Southern Ocean derived from the Southern Ocean Dietary Database. Nodes (circles) are coloured and numbered according to taxonomic groups corresponding to the name of the group listed in the key. Edge (line) widths are scaled according to the fraction of diet by weight data. The colour of the edges corresponds to the prey species/group being linked to the relevant predator node (where visible, arrow heads reinforce this direction). Dashed lines indicate there is no fraction of diet by weight data associated with the interaction within the database although it is known to occur (reproduced Figure 7 from McCormack et al., 2021a with MEASO headings).

Antarctic krill are the dominant secondary producers to the west of the Antarctic Peninsula and along the Scotia Arc in the East Pacific and Atlantic MEASO sectors. They have a lesser role elsewhere in the Antarctic Zone (McCormack et al., 2021a). Secondary producers are dominated by smaller zooplankton grazers in the Subantarctic and Northern Zones.

The main functional groups in the various Antarctic food webs are defined by size, life history, feeding ecology and habitat (Figure 9.4; Table 9.1) (Murphy et al., 2012, McCormack et al., 2021b, Melbourne-Thomas et al., 2017). In order to understand fully the role of Southern Ocean ecosystems in the Earth system, food webs must include the interaction between benthic and pelagic systems, and the role of benthos in mobilising or sequestering carbon and other nutrients.

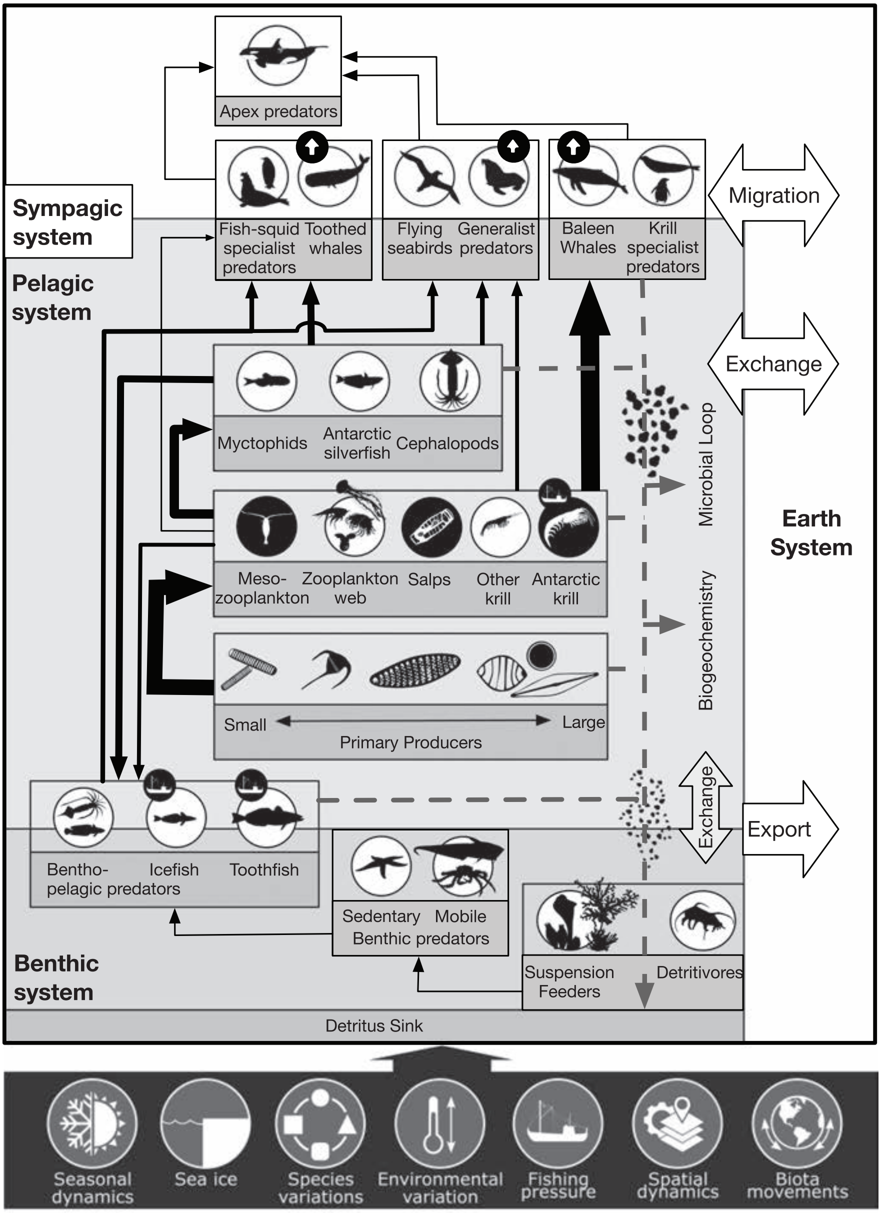

FIGURE 9.4 Network diagram showing energy flows between functional groups in Southern Ocean ecosystems (Trebilco et al., 2020, McCormack et al., 2021b). Filled circles with up arrows indicate recovering populations. Filled circles with fishing vessels indicate current fisheries. Rectangle at the bottom shows drivers of variability and change. (Icons and advice provided by Stacey McCormack, Visual Knowledge).

TABLE 9.1 Typical functional groups of different biota in the Southern Ocean, approximate size, productivity, consumption and expectations for pressures of change from future change in habitats. Annual per biomass production (P/B) and consumption (Q/B) are from standardised Ecopath models (Hill et al., 2021). Expectations for pressures for change derived from the Marine Ecosystem Assessment for the Southern Ocean (Constable et al., 2023b)

								Expected pressure for change					
Broad group	*Functional Group*	*Differentiated ecologies*	*Size (m)*	*Reprod-uctive age (log_{10}(yrs))*	*Approx. foraging range (log_{10}(m))*	*P/B*	*Q/B*	*Temp-erature*	*Acid-ification*	*Sea ice*	*Ocean processes*	*Iceberg calving; Ice sheet melt*	*Weather*
Benthos	Detritivores		0.2	0	2	0.98	11.31			↑			
	Suspension feeders		Colonial	0	–	0.98	11.31		↓	↑		↓	
	Benthic predators		0.2	0	3	0.98	11.31						
Bentho-pelagic fishes & squids	Bentho-pelagic fishes & squids	Toothfish	1.5	1	4	0.31	2.38	Mixed			Mixed		
		Icefish	0.45	0	4	0.31	2.38	↓					
		Other notothenids	0.5	0	4	0.31	2.38	Mixed			Mixed		
		Squid	1	0	4	5.28	19.09						
Protists	Bacteria		1.E−06	−3.5	–	28.98	109.13						
	Primary producers	Large diatoms	1.E−04	−2.5	–	62.3		↓			↓	↑	
		Smaller protists	1.E−05	−2.5	–	87.94		↑					
		Ice algae	1.E−05	−2.5	–	87.94				↓			
Zooplankton	Web	Microzooplankton	1.E−04	−2.5	–	37.68	154.4						
		Pteropods	1.E−02	−0.3	2	7.62	44.09	↑	↓	↑			
		Predatory amphipods	1.E−02	−0.8	2	6.21	48.17						
		Jellyfish	1.E−01	−0.8	2								
	Mesozooplankton	Copepods	1.E−03	0	2	7.62	44.09						

(Continued)

TABLE 9.1 (Continued)

								Expected pressure for change					
Broad group	*Functional Group*	*Differentiated ecologies*	*Size (m)*	*Reprod-uctive age ($\log_{10}$(yrs))*	*Approx. foraging range ($\log_{10}$(m))*	*P/B*	*Q/B*	*Temp-erature*	*Acid-ification*	*Sea ice*	*Ocean processes*	*Iceberg calving; Ice sheet melt*	*Weather*
	Macrozooplankton	Salps	0.1	−2.5	2	9.19	290.38	↑		↑	↑		
		Small krill	0.04	0	3	3.09	17.26	↓	↓	↓			
		Antarctic krill	0.06	0	4	3.09	17.26	↓	↓	↓			
Mesopelagic fishes & squids	Mesopelagic fishes & squids	Lantern fish	0.1	0	4	0.74	4.95	Ant↓ Sub↑					
		Antarctic silverfish	0.15	0	4	0.74	4.95	↓		↓			
		Cephalopods	1	0	4	5.28	19.09	↑					
Marine mammals and birds	Fish-squid specialists	Emperor/King penguins	1	0	5	0.19	30.1			Emp ↓	King ↓		
		Elephant seals	4	0	6	0.13	15.32						
		Toothed whales	16	1	6	0.04	5.61						
	Generalists	Eudyptid penguins	0.6	0	5	0.19	30.1						
		Flying birds	1	0	7	0.21	75.8						
		Antarctic fur seals	1.6	0	6	0.13	15.32						
	Krill specialists	Pygoscelid penguins	0.7	0	5	0.19	30.1			Adelie ↓			Adelie ↓
		Crabeater, pack ice seals	2	0	6	0.13	15.32			↓			
		Baleen whales	15	1	6	0.03	5.31						
	Apex Predators	Leopard seals	3	0	6	0.13	15.32						
		Orca	8	1	6	0.04	5.61						

Energy can also be moved up or down between pelagic and benthic systems via vertical migration of zooplankton, krill, fish and squid with them feeding and/or defecating at different depths as well as being eaten by predators in the different systems (Figure 9.2; Figure 9.4).

The productivity and structure of food webs and the relative importance of different energy pathways vary between areas of the Southern Ocean (McCormack et al., 2021b, Murphy et al., 2012, De Broyer et al., 2014, Knox, 2007). For the combined MEASO Areas, net primary production averaged 4.25 GT per year (±0.28 standard deviation) between 2001 and 2020, based on a recent satellite data product combining available algorithms (see methods in Ryan-Keogh et al., 2023; plus derivation of this quantity in online Supplementary Material). When compared to *in situ* float data, this is likely to be an under-estimate because satellite data do not include production under sea ice or deeper in the ocean (Stoer and Fennel, 2022, Pinkerton et al., 2021). Nevertheless, these satellite data are useful for comparing productivity of the different MEASO sectors, zones and areas (Figure 9.5a).

Total production is greater in the Northern Zone, north of the Subantarctic Front, than the other zones. In the area of the Antarctic Treaty System, total production is greater in the Subantarctic Zone than in the Antarctic Zone, except where they are equivalent in the Atlantic and West Pacific Sectors involving the Weddell and Ross gyres respectively. In the Antarctic Zone, total productivity differs greatly between sectors: Atlantic >>> Central Indian = West Pacific >> East Pacific = East Indian.

These general patterns of production mask the fact that, excluding the Northern Zone, the Atlantic Sector has only 15% more total production than the Central Indian Sector. Both of these have at least twice the total production of each of the other sectors. A great difference between these two sectors is the manner in which productivity is distributed. For the Atlantic Sector, the Scotia Arc and its islands (Scotia Arc is likely an important source of iron for oceanic systems) have an important connecting role from the Antarctic Peninsula to the northeast, coupled with gyral influences on the Antarctic coast. In contrast, the Central Indian Sector has a much weaker, though important, flow from the south to the north and a much greater contribution of zonal flows along the Antarctic coast and along the chain of subantarctic islands and across the Kerguelen Plateau (Chapter 4).

These factors and the extreme seasonality of the environment (Swadling et al., 2023) are very important for structuring the food webs, not only by the spatial relationships between productivity and the distribution of respective consumers but also by how much energy needs to be expended by a predator to obtain food. For example, foraging behaviours of marine mammals and birds play a key role in determining where the top-down pressures on food webs might occur. Seasonal migrations of whales and flying birds are well known (Murphy et al., 2021). Apart from pack-ice seals, foraging by seals and penguins is largely determined by locations of their land-based breeding colonies. These predators may be found on subantarctic islands and ice-free areas on the Antarctic continent (see Box 9.1). An analysis of all available tracking data of land-based predators (Hindell et al.,

2020) shows that, in the Atlantic Sector, these predators are more constrained than in the Central Indian Sector. They concentrate their foraging around the Scotia Arc, except for predators on Bouvet Island (Figure 0.1), which behave similarly to predators further east. In the Central Indian Sector, predators forage over large distances in the Subantarctic Zone, around the Subantarctic islands, as well as journeying to the Antarctic continent.

The *SCAR Southern Ocean Diet and Energetics Database* provides strong evidence of the differences in the food web structure between MEASO sectors (McCormack et al., 2021a) (Figure 9.3). When biomasses are standardised per unit abundance of phytoplankton, the distinctions in Figure 9.3 are also present amongst the mass-balance (Ecopath) models used to synthesise food web knowledge and characterise productivity and energy flows through the food webs around the Southern Ocean (Figure 9.5) (see McCormack et al., 2021b, Hill et al., 2021

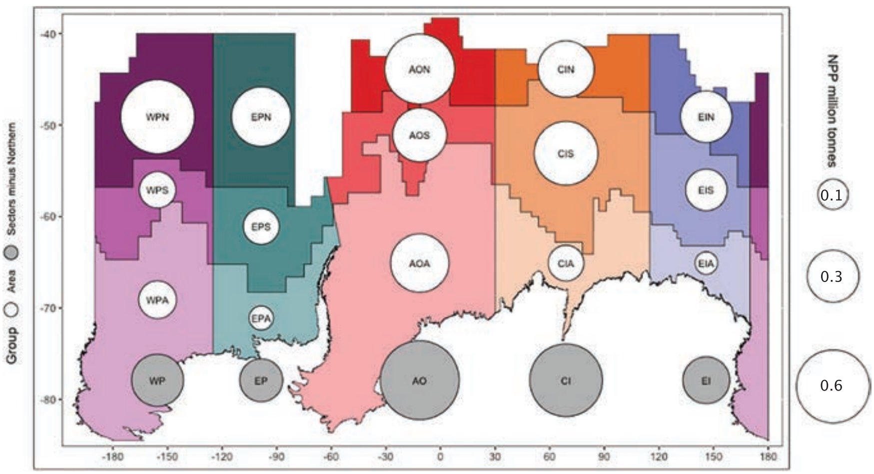

FIGURE 9.5 Spatial differences in productivity and food webs in the Southern Ocean. (a, above) Mean annual net primary productivity from combined metrics of production (2001–2020) (data from Ryan-Keogh et al., 2023), for each MEASO Area (see Figure 9.2 for meanings of acronyms), as well as combined for each sector excluding the Northern Zone (all means: CV<0.2; see online Supplementary Material). (b, next page) Biomass of different taxa relative to protist biomass estimated in different Ecopath models: East Pacific Antarctic – West Antarctic Peninsula North (EPA-APN, Dahood et al., 2019) and South (EPA-APS, Ballerini et al., 2014), Atlantic Subantarctic (AOS; Scotia Arc, Hill et al., 2012), Central Indian Antarctic (CIA; Prydz Bay, McCormack et al., 2020), Central Indian Subantarctic (CIS; Kerguelen Plateau, Subramaniam et al., 2020), Central Indian Northern (CIN; Prince Edward-Marion, Gurney et al., 2014), West Pacific Antarctic (WPA; Ross Sea, Pinkerton et al., 2010). Inset: non-metric multidimensional scaling showing the degree of differences between food-web structures in the Ecopath models (stress <0.001, colours relate to sectors in (a); see online Supplementary Materials)

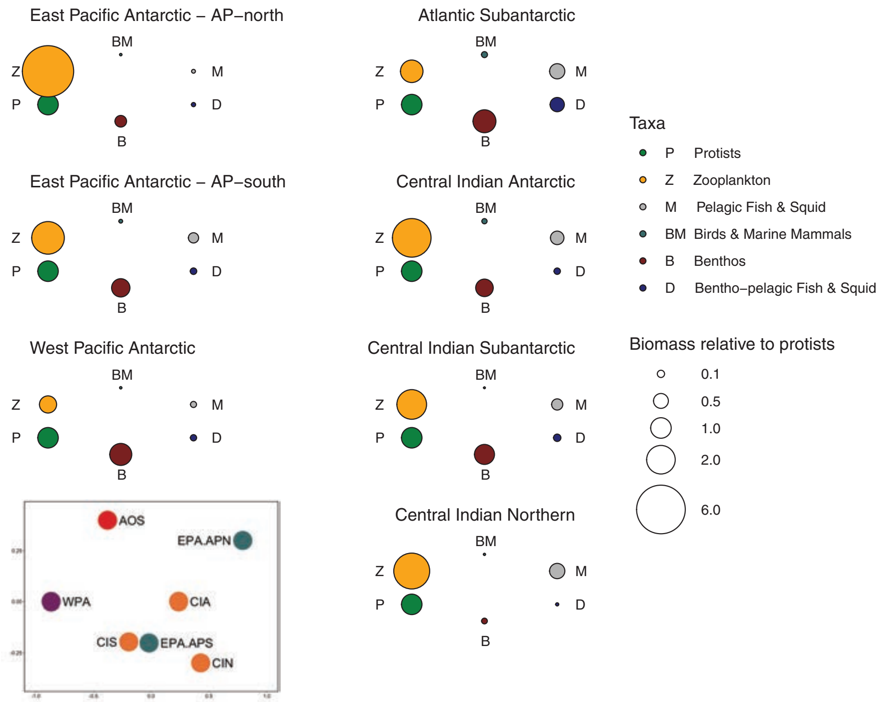

FIGURE 9.5 (Continued)

for review). The dissimilarity between Ecopath models (Figure 9.5b) indicates differences in the relative importance of zooplankton and Antarctic krill (left to right gradient) and differences in the types and abundances of bentho-pelagic fish and top predators (bottom to top gradient). The following characteristics of food webs were derived from these two different analyses.

When viewed together, the northern model for the West Antarctic Peninsula (around the South Shetland Islands) and the model for Atlantic Subantarctic area (Figure 9.5b) show a complete picture expected of the spatially connected krill-based system (Murphy et al., 2013), with the Subantarctic area having a greater mass of higher trophic species feeding on krill transported from the Antarctic Peninsula and Weddell Sea (Atlantic Antarctic area).

The southern model for the West Antarctic Peninsula (around Marguerite Bay) has similarities in the distribution of mass between groups as the Central Indian Antarctic model, suggesting a more widespread complex pelagic-benthic system together with sea ice and multiple energy pathways in the Amundsen–Bellingshausen Seas and East Antarctica.

Relative to primary production, the Central Indian Antarctic area (Prydz Bay and southern Kerguelen Plateau), with its complex food web (Figure 9.3), sustains large biomasses of higher trophic levels and benthos (Figure 9.5b). This suggests a more efficient food web than those in the subantarctic or northern areas of that sector, which rely on the less productive energy pathway through copepods and mesopelagic fish (McCormack et al., 2021b, Trebilco et al., 2020). More, this also indicates greater recycling of nutrients overall, such as can be expected through whales and other higher trophic levels assisting with iron recycling (Ratnarajah et al., 2018), and by the processing of waste by bacteria (Henley et al., 2020).

In contrast, the West Pacific Antarctic (Ross Sea) model shows a dominance of lower trophic levels and the benthic system, including benthic fish, compared with less biomass of pelagic fish, squid, birds and marine mammals. This indicates a diversion of energy at lower trophic levels into the benthic system. In the Ross Sea, pelagic primary producers are dominated by *Phaeocystis* (Arrigo et al., 2003), which is not palatable to krill (Johnston et al., 2022). A large proportion of *Phaeocystis* is ungrazed and sinks to the benthos (Pinkerton and Bradford-Grieve, 2010). Perhaps the Weddell Sea food web has similar attributes given it has a similar extreme polar environment.

All models show the importance of benthos and demersal fish in the system, having important roles as carbon pools (Bax et al., 2021), and these models suggest they may be greater than marine mammals and birds at present (Figure 9.5). Moreover, a conclusion from this analysis is that, for most of the Antarctic Zone and the remainder of the Southern Ocean, understanding the dynamics of Antarctic marine food webs requires much more than understanding Antarctic krill and the krill energy pathway.

BOX 9.1 TERRESTRIAL ANTARCTIC ECOSYSTEMS

The Antarctic continent has terrestrial and freshwater ecosystems scattered around the coastal margins along with large ice-free areas associated with the Trans-Antarctic Mountains and other mountain ranges and peaks (Chown et al., 2022). In total, these areas comprise 0.4% of the Antarctic continent. These rocky outcrops, including the interior, have summer colonies of many migratory birds, although the largest colonies of marine predators are at the coast for the Antarctic breeding season, comprising flying birds, penguins and seals. While the continent is vast, ice-free areas within 5 km of the coast comprise less than 12,000 km^2 (equating to less than the coastline of Tasmania, Australia) (Figure B9.1.1). Currently, the greatest area of terrestrial habitat near the coast is on the Antarctic Peninsula and nearby islands, which is also the area where the greatest expansion of habitat is expected to occur over the remainder of this century (Lee et al., 2017).

Vegetations in terrestrial habitats mostly comprise mosses and lichens, along with algae in moist and lake environments (Chown et al., 2022). Vascular plants (grasses) occur on subantarctic islands and non-native plants are invading a number of areas, particularly on the Antarctic Peninsula. Vegetated

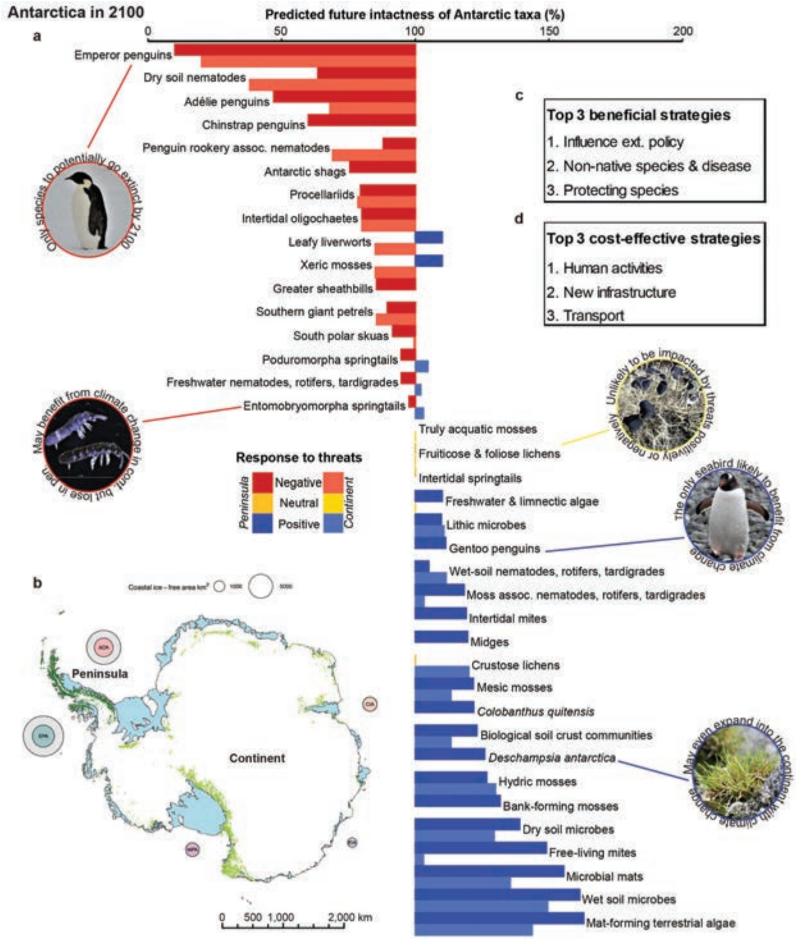

FIGURE B9.1.1 Expert judgement of the vulnerability of terrestrial Antarctic biodiversity threatened under climate forcing scenario RCP8.5 (business as usual), including expert identification of management strategies (expert workshop results, reproduced from Figure 1 in Lee et al., 2022). (a) Regional vulnerability of biodiversity groups (expected response to threats shown by darker/lighter bars denoting relative responses on Peninsula or Continent: bars represent experts' estimate of future intactness of each taxon relative to current (100%) intactness (vulnerable are < 100%; benefit are >100%). (b) Areas of suitable habitat on the Continent (light green) and Antarctic Peninsula (dark green). This map was supplemented with analysis of the area (km^2) of ice-free habitat within 5 km of the coast in MEASO areas (using results from Lee et al., 2017, coloured circles are the current area, grey circles are the predicted area for 2100) (colours and symbols as in Figure 9.2). (c) The top three individual management strategies that would provide the highest total benefit to biodiversity. (d) The top three most cost-effective strategies for conserving biodiversity.

areas support the greatest diversity of terrestrial animals, comprising mites, tardigrades, nematodes, insects and collembolids (Chown et al., 2022). Unvegetated areas are dominated by microbes and infauna (organisms living within the earth). All ice-free habitats have now been classified into 16 bioregions (Terauds et al., 2016).

Other than temperature impacting the physiology of Antarctic species (Chown et al., 2022), three important changes are occurring: the expansion of habitat through melting of perennial ice (Lee et al., 2017), the increase in precipitation and warming of the soils leading to "greening" on the Antarctic Peninsula (Constable et al., 2022), and increased drying in many regions, including prolonged heatwaves, leading to dramatic changes in vegetation (Robinson et al., 2018, Chown et al., 2022). Given the paucity of ecological studies in the terrestrial biome, relevant experts have used their knowledge to develop expectations for change in different taxa found in terrestrial habitats of the Antarctic Peninsula and the remainder of the continent (Lee et al., 2022)(see Figure B9.1.1).

9.3 Direct Impacts of Fisheries

Southern Ocean ecosystems have been influenced by people since Europeans discovered seals in the region (Chapter 10). The main phases of influence have been sealing, industrial whaling, ozone depletion and climate change, finfish fishing and the modern era (Morley et al., 2020, Grant et al., 2021). Except for climate change (see Section 9.5), uncontrolled large-scale impacts ended with the moratorium on commercial whaling in 1986 and the adoption of the precautionary approach to fishing instigated under the Convention on the Conservation of Antarctic Marine Living Resources (CAMLRC) by its Commission (CCAMLR) and the adoption of the Protocol to the Antarctic Treaty on Environmental Protection, both in 1991, although it was another 15 years to control illegal, unregulated and unreported fishing and impacts on seabirds. By comparison, impacts of national activities and tourism have been locally contained (Grant et al., 2021), but those impacts need to be measured relative to the magnitude of available ice-free and adjacent subtidal areas rather than compared to Antarctica as a whole (Box 9.1).

Research is relatively recent compared to the history of anthropogenic perturbations (Brasier et al., 2019). Reconstructions of trajectories use Earth system and individual species modelling, combined with specific knowledge on the ecology of species (Table 9.1).

The near extirpation of Antarctic fur seals and many species of whales had been regarded as possibly giving rise to a surplus of krill. However, early food web modelling suggested it was more likely that other krill predators would have increased in abundance from exploiting the excess (Murphy, 1995). Greater understanding of biogeochemical cycles has revealed that the depletion of baleen whales may have diminished the recycling of iron with consequent decreases in annual primary production,

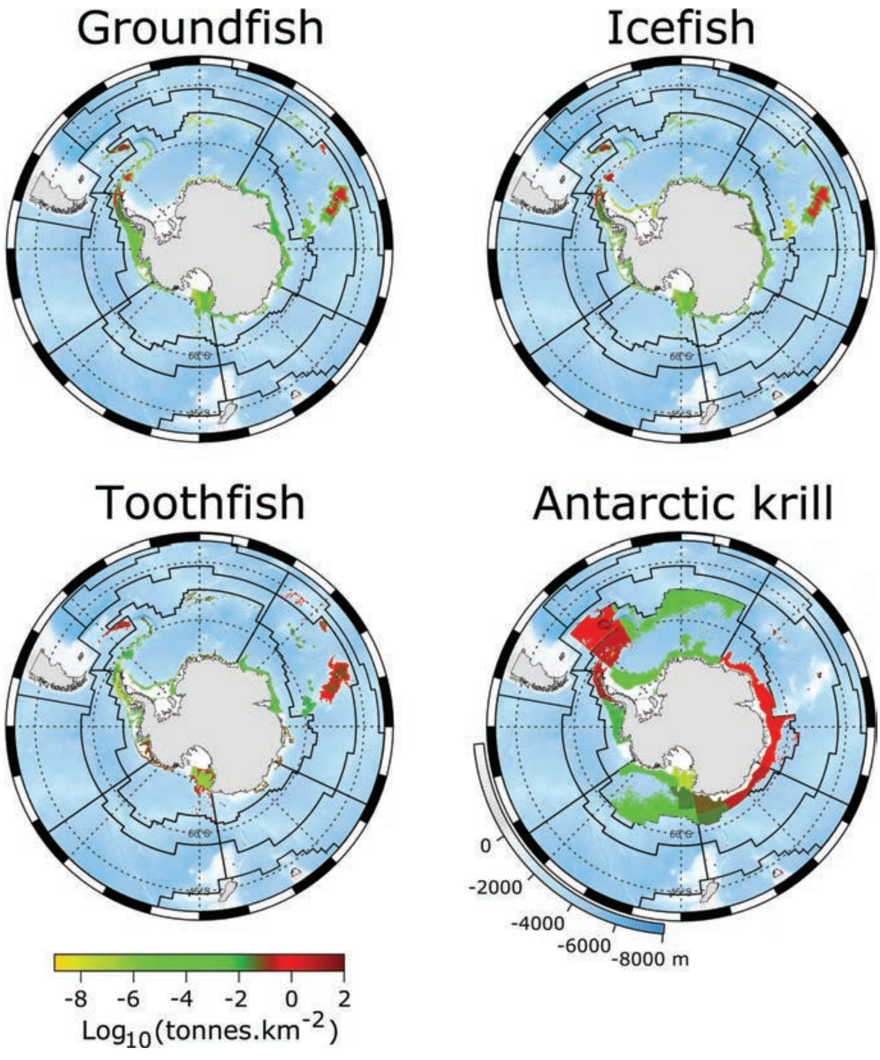

FIGURE 9.6 Historical fishing footprint in the Southern Ocean. Accumulated catch for groundfish, icefish, toothfish and Antarctic krill from 1970 to 2018 plotted against ocean depth (legend at bottom left of Antarctic krill panel) as catch density (tonnes per square kilometre) on a $\log_{10}$ scale (bottom left legend). Source data: CCAMLR Statistical Bulletin 2019. Grey lines show a graticule, and black lines show the boundaries of the 15 MEASO areas (with permission from Grant et al., 2021)

thereby reducing krill abundance and the potential for carbon sequestration in the Southern Ocean (Savoca et al., 2021, Cavan et al., 2019, Grant et al., 2021).

Little is known of the effects of the depletion of demersal finfish by trawlers from shelf areas around subantarctic islands, the Antarctic Peninsula and some of the other continental shelf areas around Antarctica (Figure 9.6) but those fisheries would have altered predator–prey dynamics in the shelf system (Kock and Jones, 2007), including by the large amount of bottom scouring caused by the bottom trawling (Grant et al., 2021, Brasier et al., 2021).

Globally, albatross and petrels have suffered substantial declines from being caught in longline fisheries, including in the Southern Ocean (Grant et al., 2021). By 2010, bycatch of these endangered species had been more-or-less eliminated from the CAMLRC Area (Grant et al., 2021), although Southern Ocean species remain at risk from fisheries elsewhere (Clay et al., 2019).

9.4 Managing Risks from Antarctic Krill Fisheries

Parties to CAMLRC recognise, first and foremost, "*the importance of safeguarding the environment and protecting the integrity of the ecosystem of the seas surrounding Antarctica*" (CAMLRC, 1st Preambular paragraph). Through the various legal instruments, conservation is the primary objective and a precautionary approach should be taken – maintaining a high likelihood that conservation will be achieved using the best available science and taking account of uncertainty in that science (Hughes et al., 2018, CCAMLR Performance Review Panel, 2017).

Mechanisms for managing the effects of fishing have been reviewed extensively elsewhere (Constable, 2000, Kock et al., 2007, Constable, 2011, CCAMLR Performance Review Panel, 2017). Instead, this section focuses on how CCAMLR is approaching the management of the fishery for Antarctic krill, a lynchpin of the Antarctic Zone, which set up the approaches now adopted for the other fisheries (Kock et al., 2007). It provides the detail necessary to understand the complexity of taking a precautionary and ecosystem approach to manage fisheries, how the pace of advancing management of the krill fishery has been much slower than anticipated at the genesis of CAMLRC, termed at the time as the "Krill Convention", and how the early safeguards for maintaining an orderly development of the fishery remain significant for maintaining Southern Ocean ecosystems.

9.4.1 Principles for Managing Fisheries

CAMLRC has specific conservation requirements in relation to fisheries (Constable et al., 2000), hereafter referred to as the CAMLRC Fishery Principles (Article II, Paragraph 3):

i Targeted stocks must not be reduced "*to levels below those which ensure its stable recruitment*" or "*allowed to fall below a level close to that which ensures the greatest net annual increment*";
ii Fisheries should not alter ecosystem structure and function, with particular reference to maintaining ecological relationships between harvested, dependent and related populations;
iii Restoration of depleted populations (whales, seals and finfish) should not be impeded; and

iv Impacts of fishing should be reversible over two or three decades.

CAMLRC was negotiated amidst a fear that harvesting Antarctic krill could lead to irreversible changes in Antarctic ecosystems. These principles captured the important elements of what are now known as the precautionary and ecosystem approaches to fisheries management in the region.

For CCAMLR, the Fishery Principles were made operational in the work of the Working Group on Developing Approaches to Conservation and in working groups of the Scientific Committee of CCAMLR (Constable et al., 2000).

Importantly, in 1991 (CCAMLR, 1991, paragraph 6.13):

> *6.13 …. The Commission endorsed the advice of the Scientific Committee that reactive management - the practice of taking management action when the need for it has become apparent - is not a viable long-term strategy for the krill fishery. Some form of feedback management, which involves the continuous adjustment of management measures in response to information, is to be preferred as a long-term strategy. In the interim, a precautionary approach is desirable and in particular, a precautionary limit on annual catches should be considered.*

In that year, CCAMLR began establishing Conservation Measures to regulate the fishery, using its precautionary approach (see progress in Table 9.2). Since then, the Scientific Committee has worked to refine this approach as well as develop a feedback management procedure for the krill fishery. The question for feedback management is what measures of the ecosystem are required to enable adjustment of the harvest strategy in order to avoid failing to satisfy the Fishery Principles? Two subsidiary questions arise: (i) what information is needed to enable catch limits to increase, and (ii) what field monitoring is needed to assess whether catches are too high, in advance of problems arising?

Operational definitions and concepts made it possible to develop a rule for deciding on krill catch limits. The rule was developed to decide a long-term annual catch that would take the krill stock down from pre-exploitation levels to a target level. The rule comprised three parts (see CCAMLR Secretariat, 2020, for exact wording). First, the median expectation for the krill spawning biomass at the end of a 20-year projection period would not be less than the target level (higher than for single species management and allowing escapement for needs of predators), set as 75% of the pre-exploitation median. Second, the chance that the spawning stock falls below a limit (avoid stock depletion and unstable recruitment), set at 20% of that pre-exploitation median, should be no more than 10%. Last, what is the maximum catch, as a proportion of a survey biomass estimate, that would satisfy both criteria? This proportion is known as *Gamma*. The target level is currently *ad hoc* and remains to be determined (Kock et al., 2007). Figure 9.7a shows the expectation for the krill spawning stock after harvest begins, and then the expected recovery within 20–30 years if it should end.

TABLE 9.2 Development of CCAMLR regulatory (Conservation) measures (CMs) related to catch limits and scientific observations for the krill fishery, which mostly occurs in the MEASO Antarctic Zone. Area 48 relates to the West Antarctic Peninsula in the MEASO East Pacific Sector, and the MEASO Atlantic Sector. Division 58.4.2 relates to the MEASO Central Indian Sector. Division 58.4.1 relates to the MEASO East Indian Sector. Ongoing CMs do not have an end date. Continuing CMs are renegotiated at the end of the period specified in the measure

	1982–1994	*1995–2004*	*2005–2014*	*2015–2024*
Development of fishery	**Area 48** (1991 – CM 32/X): ongoing as CM 51-01. Fishery not to exceed 0.62mt without further precautionary limits in small areas.	**Area 48** (2000, CM 32/XIX) Trigger level maintained	Trigger level defined (2007) **Area 48** (2007, CM51-01) **Division 58.4.2** (0.452mt, 2007, CM 51-03) **General** measure for exploratory krill fisheries (2008, CM 51-04, ongoing)	CM 51-01 ongoing CM 51-03 ongoing CM 51-04 ongoing
Annual catch limit (million tonnes – mt)	**Area 48** (1.5mt, 1991, CM 32/X) **Division 58.4.2** (0.39mt, 1992, CM 45/XI)	**Area 48** (4mt, 2000; CM 32/XIX) **Division 58.4.1** (0.775mt, 1996, CM 106/XV; 0.44mt, 2000, CM 106/XIX, & 2002, CM 51-02) **Division 58.4.2** (0.45mt, 1995, CM 45/XIV; 2002, CM 51-03)	**Area 48** (3.47mt, 2007; 5.61mt, 2010; CM 51-01) CM 51-02 ongoing **Division 58.4.2** (2.645mt, 2007, CM 51-03)	CM 51-01 ongoing CM 51-02 ongoing CM 51-03 ongoing
Spatial subdivision of catch limit	**Area 48** Subarea limits in Area 48 (CM 46/XI, lapsed in 1994)	**Area 48** Subarea limits included in CM 32/XIX) subject to maximum Trigger Level without limits in smaller areas **Division 58.4.1** divided into two areas (2000, CM 106/XIX & 2002, CM 51-02)	**Area 48** Interim subdivision of Trigger Level amongst Subareas (2009–2014; CM 51-07) CM 51-02 ongoing **Division 58.4.2** divided into two areas (2007, CM 51-03)	CM 51-07 continues (2015–2024) CM 51-02 ongoing CM 51-03 ongoing
Fisheries observation			**General** observation scheme developed in CM 51-06 from 2009.	CM 51-06 continues

Source: https://www.ccamlr.org/en/conservation-and-management/conservation-measures.

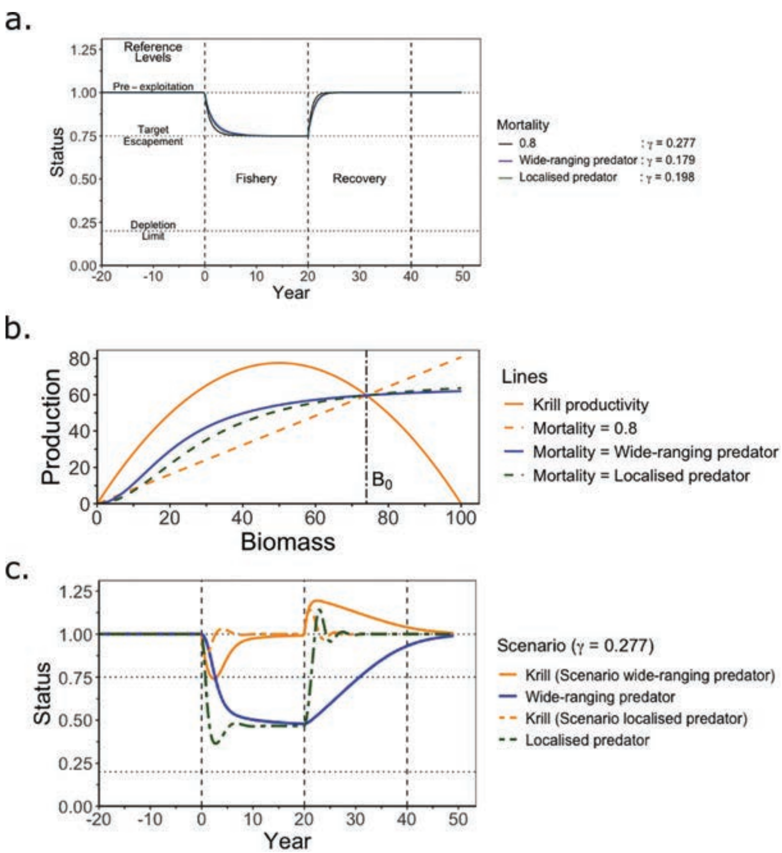

FIGURE 9.7 Theoretical considerations of the CCAMLR rule for deciding catch limits for the Antarctic krill fishery. (a) Expectations in the CCAMLR yield model of a catch limit derived from Gamma(γ) times a survey estimate of pre-exploitation biomass (B_0) for deterministic biomass projections of Antarctic krill based on the Pella-Tomlinson production model and mortality functions in (b). Gamma is associated with each curve provided in the legend. Status is the krill biomass relative to the pre-exploitation level. Fishing occurs during the fishery period followed by a recovery period. See the text for details on the different reference levels and the recovery period. (b) Pella-Tomlinson production model based on maximum production to biomass ratio (r) for Antarctic krill of 2.0 yr^{-1}. Mortality functions are a constant instantaneous mortality rate (0.8 yr^{-1}; constant M) and two examples of a Holling Type III functional feeding relationship – a wide-ranging predator able to continue to find prey, and a localised predator that has greater difficulty finding prey as the prey decline. Mortalities from all functions are expected to be equal if the pre-exploitation population is in equilibrium. (c) Projections of a dynamic predator–krill model under constant catch from a CCAMLR-like assessment using constant M. Krill are modelled using the Pella-Tomlinson productivity model and krill mortality from consumption of krill by the predator. The predator biomass is modelled using Ecopath parameters of consumption, production, respiration and mortality from Hill et al. (2021). Consumption is varied according to the functional feeding relationships in (b). Two scenarios were projected – the wide-ranging predator used parameters for baleen whales; the localised predators used parameters for penguins (see online Supplementary Material for details).

In adopting the advice of the Scientific Committee to establish a catch limit for krill in Area 48 (covering the northern part of the Antarctic Peninsula and the Atlantic Sector; Chapter 10) in 1991, CCAMLR also established a cap on the fishery at historical catch levels, now known as the trigger level, and "requested the Scientific Committee, as a matter of priority, to advise the Commission on precautionary catch limits by subarea and, where it considers appropriate, on finer spatial scales" (CCAMLR, 1991, paragraph 6.17). This cap was established because of advice from the Scientific Committee to avoid the fishery concentrating in areas and disproportionately affecting sources of krill upstream in Area 48 or land-breeding predators.

The remainder of this section presents issues remaining to be resolved for establishing a suitable ecosystem-based harvest regime for krill, all of which need consideration before the fisheries expand beyond the trigger levels.

9.4.2 Productivity and Recruitment of Krill

Antarctic krill are known to be very productive and highly responsive to primary productivity in an area (Constable and Kawaguchi, 2017, Ryabov et al., 2017). Recent standardisation of Ecopath models suggests annual new productivity per krill biomass of around 3.0 $year^{-1}$ (Hill et al., 2021), at the high end of the range of historical values (Siegel and Watkins, 2016). Generally, catch limits are positively correlated with productivity. The current growth model in the CCAMLR yield assessment is indicative of annual productivity of approximately 1 yr^{-1}.

Long-term annual yield calculations are sensitive to recruitment variability. Greater variability means a greater chance the spawning stock falls below the depletion limit. Recent analyses of time series of krill surveys around the South Shetland Islands (Conroy et al., 2020, Reiss, 2016) combined with improved methods for estimating recruitment (Pavez et al., 2023) are showing much greater recruitment variability than that used in the most recent assessment; the current *Gamma* may be three times too high, at least around the South Shetland Islands (SC-CAMLR, 2022 Annex 9 Working Group on Fish Stock Assessment).

The first issue (see Table 9.3 for details of the issues) relates to the application of the decision rule and whether the measurement of the target level in the rule satisfactorily accounts for the variability, uncertainty and trajectory of the krill stock. In using the rule, will the median biomass of the stock, in reality, remain at or above the target level over time? A second issue arises as to whether the depletion limit satisfactorily avoids unstable recruitment.

9.4.3 Maintenance of Krill Predators

The third issue relates to the target escapement level for krill, and whether it will enable predators to not be unduly affected by fishing (Hofman, 2016). Aside from climate change, Antarctic krill fisheries remain the greatest challenge for the

Commission (Constable, 2006, 2011) because the needs of predators remain to be determined, despite work in the 1990s (Thomson et al., 2000). What will happen to the food web if 9.3% (current *Gamma*) of an estimate of biomass is removed each year (Watters et al., 2013, Plaganyi and Butterworth, 2012)? Will the predators be able to recover within 20–30 years should fishing cease (Constable and Candy, 2008)? The answers very much depend on the productivity and spatial ecology of krill and the life histories and feeding ecologies of the predators (Boyd et al., 2006, Constable, 2001).

The fourth issue relates to whether the representation of mortality in the krill assessment is appropriate. Currently, the instantaneous mortality rate for krill in the krill assessment is around 0.8 $year^{-1}$ (Reiss, 2016, SC-CAMLR, 2023 Annex 8). This constant mortality rate for krill is equivalent to a Type I Holling functional feeding relationship of predator consumption relative to prey abundance. For prey species, like krill, these relationships are expected to be Type II or, as illustrated, Type III (Figure 9.7b) because predators can maintain consumption as the krill population declines (de la Mare et al., 2018). Such mortality functions can be expected for krill because krill continue to maintain swarms at lower abundances (Brierley and Cox, 2015). Assuming a Type I functional relationship means that krill mortality will be underestimated as the population declines, leading to overharvesting because the fishery will be allocated productivity that is needed by predators (Figure 9.7a). In the language of the decision rule, *Gamma* would be expected to be lower for a Type III functional relationship, because escapement for predators needs to be higher as the target level is reached.

Changing the mortality function and target level will not satisfactorily resolve the consideration of predators in managing the krill fishery. Abundances of krill predators are likely to be reduced unless they switch to alternative prey (Watters et al., 2013, Plaganyi and Butterworth, 2012, Klein and Watters, 2020). Thus, the fifth issue relates to the efficacy of having a krill-centred rule, given krill mortality will be dependent on the predator ecologies and responses. For example, could predators be replaced by the fishery, resulting in krill biomass being a relatively insensitive indicator of the food web in the long term (Figure 9.7c)? The sixth issue extends this concern to the recovery of whales (Tulloch et al., 2018) and Antarctic fur seals (Forcada et al., 2023, Krause et al., 2024), because recovery may be complicated in that fishing and climate change need to be considered as threats to continued recovery. Moreover, when will recovery be considered as having been achieved?

9.4.4 Climate Change and Ocean Acidification

Climate change and ocean acidification together constitute the seventh issue because they may cause declines in populations of Antarctic krill, resulting from reduced growth and reproduction from higher temperatures and lower food, reduced hatching success from ocean acidification and lower recruitment as a result of declines in sea ice (Johnston et al., 2022). Further, declining productivity in krill can result in increased risk of declines in predators (Klein et al., 2018). To date, climate change has not been factored in to the krill assessment.

9.4.5 Accounting for Spatial Structure of the Ecosystem

The cap on the krill fishery is intended to trigger finer-scale catch limits to ensure that the spatial structure of the krill population and predators are not unduly and disproportionately affected by concentrations of the fishery, i.e. that the impact on krill and predators would simply be from a reduction in total krill production available to them (Constable, 2006, Constable, 2011, SC-CAMLR, 2011 Annex 4). This concern gave rise to catch limits at the subarea scale in 2000 followed by adoption in 2002 of small-scale management units for a finer-scale division of the total catch upon advice of the Scientific Committee (CCAMLR, 2002, paragraphs 4.5–4.9). However, these subarea limits are only a temporary Conservation Measure renegotiated every two years, despite concerns that even current catches below the trigger level may impact penguins (Watters et al., 2020). An agreement on finer-scale catch limits is yet to be reached (CCAMLR, 2023). However, in 2016, an approach to distribute the catch amongst smaller areas in a manner that would reduce overlap with important source areas of the krill population and areas important to predators (high predation pressure) was adopted (Constable et al., 2023a, SC-CAMLR, 2016, CCAMLR, 2016). This method is intended for revision as assessments of risks to krill stocks and predators improve; such knowledge is a prerequisite for expanding the fishery (Constable et al., 2023a). The eighth issue, therefore, concerns how often spatial overlap needs to be reassessed as the food web adjusts to the fishery.

9.4.6 Approaches and Field Monitoring to Address the Issues

The eight outstanding issues and their subsidiary questions to be considered before raising catches above the trigger levels are laid out in Table 9.3. Approaches for addressing these issues are also summarised, most of which require using population and ecosystem models, along with evaluating the performance of management strategies given the respective uncertainties (Section 9.6.1). Suggested field monitoring for assisting assessments of appropriate harvest strategies in advance of raising the trigger level and/or maintaining feedback management checks that the harvest strategy remains satisfactory are also provided.

9.5 Recovery and Climate Change

The observed increases in humpback whales and Antarctic fur seals suggest resilient ecosystems in the Southern Ocean, but those recoveries have been many decades in the making (Bestley et al., 2020). Humpback whales are at approximately 70% of pre-exploitation abundance (Bamford et al., 2023), and Antarctic fur seals have substantially increased, but whether they have recovered is yet to be determined (Forcada et al., 2023). The still poor recovery of other whales (Bestley et al., 2020, Bamford et al., 2023) and groundfish (Kock and Jones, 2007, Duhamel and Williams, 2011, Maschette et al., 2024) shows a system that only recalibrates over many decades if not a hundred years (Murphy, 1995, Tulloch et al., 2018).

There is no doubt that lower trophic levels are changing in both productivity and relative importance of different phytoplankton and zooplankton groups in different places (Pinkerton et al., 2021, Johnston et al., 2022). Concomitant changes are being observed in some higher trophic level taxa, most notably demonstrated in penguins to the west of the Antarctic Peninsula, with ice-related species declining and more open-water species increasing (Constable et al., 2016b).

Habitat modelling, along with field and laboratory work, has been showing the extent to which ranges of Antarctic krill and other species are likely to contract towards Antarctica due to warming, ocean acidification and shifting production over recent times (Figure 9.2) and into the future (Johnston et al., 2022, Atkinson et al., 2022). Whether Antarctic krill are limited in how far south they can recede will depend on the need for their eggs to sink to depths deeper than the continental shelf (Green et al., 2023).

Changes in food webs may not just be from shifts in production. Higher trophic levels and benthic species may be directly impacted by shifts in the polar environment itself (Constable et al., 2023b), such as is exemplified by the drowning of chicks of emperor penguins from the break-up of their fast ice breeding habitat (Fretwell et al., 2023, Fretwell, 2024), reproductive failure due to effects of increasing late spring snowfall on nesting Adélie penguins (Fraser et al., 2013), the increased scouring of the seafloor by a greater number of icebergs (Brasier et al., 2021) or perhaps by changing phenologies (Cimino et al., 2023, Trathan et al., 2022).

Velocities of environmental change in the different MEASO areas for the productive spring period (November–December) are shown in Figure 9.8. Here, the combined effects of change in photosynthetically active radiation, mixed layer depth, sea temperature (0–2000m) and sea ice concentration are evident from 1900 to 2100, using outputs from the Earth system model, ACCESS ESM1.5 SSP5–8.5 (business-as-usual scenario) (Ziehn et al., 2020) (see online Supplementary Material). Velocities are greatest in the Antarctic zone directed towards subantarctic conditions, with the West Pacific (Ross Sea), Atlantic (Weddell Sea) and Central Indian (Prydz Bay) Antarctic areas exhibiting potential losses in their sea ice coverage (Figure 9.2). These plots also show present acceleration of change away from pre-industrial conditions.

While lower trophic levels and cephalopods have high turnovers and are very responsive to changes in production and habitats (Pinkerton et al., 2021, Johnston et al., 2022, Caccavo et al., 2021), many fish (Caccavo et al., 2021), benthic species (Brasier et al., 2021), marine mammals and birds (Bestley et al., 2020) are long-lived with much lower turnover rates and, therefore, are much slower to recover (lower resilience) from perturbations (De Broyer et al., 2014) (Table 9.1).

The Antarctic Zone is especially vulnerable to climate change and ocean acidification (Constable et al., 2016b). Many Antarctic marine species are cold- and/or

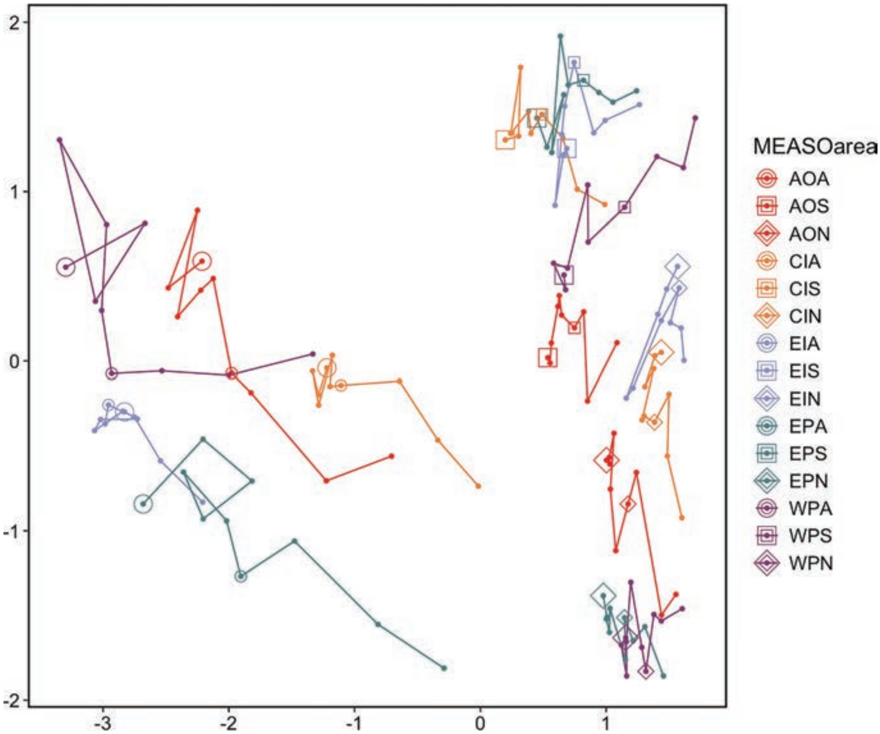

FIGURE 9.8 Illustration of velocity of changes in the physical environment of each MEASO area (acronyms detailed in Figure 9.2) projected from 1900 (large symbols) to 2020 (small symbols) to 2100 using outputs from Earth system projections using ACCESS ESM1.5 SSP5-8.5 (business-as-usual) (Ziehn et al., 2020). Non-metric multidimensional scaling is used to plot the similarities of two-decade periods in their mean conditions for austral spring (November–December; a period of peak production) of photosynthetically active radiation, surface temperature, mixed layer depth and sea ice concentration (stress <0.001; see online Supplementary Material).

ice-adapted (De Broyer et al., 2014). In addition, sea ice plays a significant role in the life histories, productivity and/or foraging ecology of many species (Swadling et al., 2023). A future confounding effect will be the potential for invasions by non-Antarctic species, particularly in the benthic system (Brasier et al., 2021) (Box 9.2).

With climate change, ocean acidification, and the continuing recovery of marine mammals, we now need to think of the Antarctic marine ecosystem in perpetual recalibration, and that reversal of changes may not be possible on human-relevant timescales. This is definitely not to forego the need for species to recover (Section 9.6) but to recognise that lower trophic levels are likely to be responding to contemporary environmental change as well as experiencing pressures from higher trophic levels not yet calibrated to the newer conditions. Care will be needed in interpreting short-term changes because of this intermix of current and historical pressures. Shorter-lived higher trophic species, such as penguins, will likely respond to changes more rapidly than longer-lived species, like whales (Klein et al., 2018, Tulloch et al., 2019) (Figure 9.7).

BOX 9.2 NON-ANTARCTIC SPECIES

The invasion of Antarctic environments by non-native species has long been feared, especially as the region warms and traffic to and within it increases (Frenot et al., 2005, Hughes et al., 2015, McCarthy et al., 2019) (Figure B9. 2.1). Non-native terrestrial species have been discovered near research stations, particularly on the Antarctic Peninsula (Chown et al., 2022, Bergstrom, 2022). While non-native marine species have been encountered on hulls of ships, five species have been found freely living near stations with two species, an alga and a sessile invertebrate, in any abundance (Chown et al., 2022, Bergstrom, 2022).

Climate change is regarded as making southward range expansions and invasions a greater possibility (Chown et al., 2022). Typical poleward expansion of ranges of temperate and subantarctic species is more likely for pelagic organisms than benthic ones because of the separation of shallower areas by abyssal plains. However, a possible form of range expansion is by hopping between shallow areas on floating kelp rafts (Fraser et al., 2018, Fraser et al., 2022), on which marine invertebrates from northern benthic environments have been found on rafts beached in Antarctica (Avila et al., 2020, Fraser et al., 2022). As for invasions via ship traffic, recent modelling has shown that invasions through drifting from continents to the north of the Subtropical Front are most likely to occur on the Antarctic Peninsula (Dawson et al., 2024).

The likelihood of invasions is poorly understood and whether invasive marine species could disrupt food webs is unknown. A recent debate on whether lithodid shell-crushing crabs have invaded/recolonised shelf areas in the West Antarctic Peninsula (Thatje et al., 2005, Smith et al., 2012) or whether they have been present but poorly surveyed (Griffiths et al., 2013) is indicative of the difficulties of addressing this question.

Hughes et al. (2020) undertook an expert analysis to identify species that present a high risk for invasion and pose a risk to biodiversity and ecosystems in the Antarctic Peninsula Region, which is the region most likely to be invaded over the next decade. They identified 13 species, with marine invertebrates (crabs, mussels, worms, ascidians) dominating the list, and some representation of flowering plants and terrestrial invertebrates. The use of ocean models and pathway analyses are useful for better understanding risks and possible preventative actions (Fraser et al., 2022, Bayley et al., 2024, Holland et al., 2021, Dawson et al., 2024).

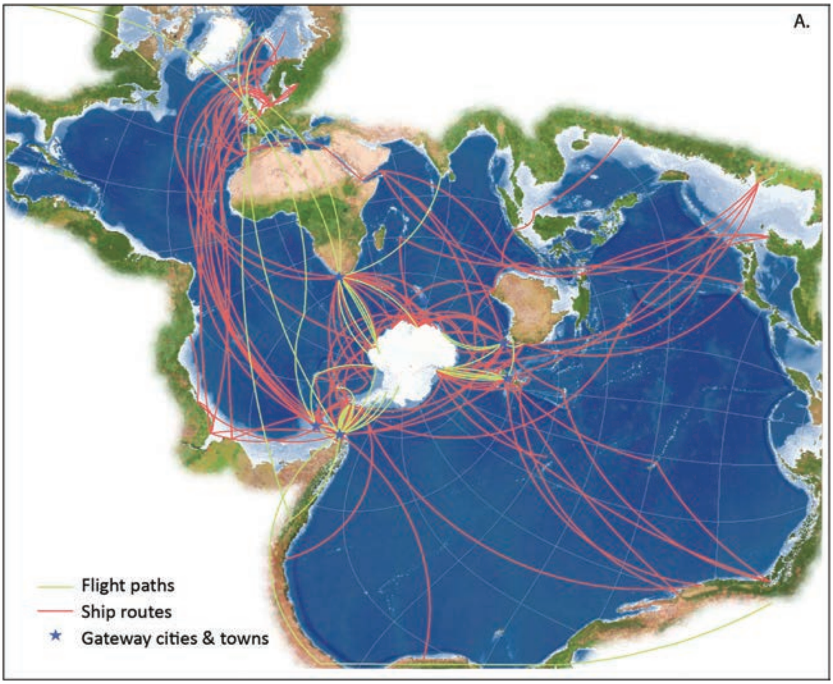

FIGURE B9.2.1 *Traffic to Antarctica via ships and aircraft* (2017–2021) (reproduced Figure 1A from Bergstrom, 2022, with permission from Elsevier).

9.6 Strategies to Meet the Challenges

The adoption of the precautionary approach to fisheries by CCAMLR in 1991 was an interim step to a more complete management system. The ability of the Antarctic Treaty System to avoid failing to meet the conservation objective for Southern Ocean ecosystems is challenged by the likely demands to expand the krill fishery (Kawaguchi and Nicol, 2020, Nicol and Foster, 2016), and the very real threats of climate change and ocean acidification (Kawaguchi et al., 2024, Constable et al., 2023b). The risks are fraught because of gaps in science and inertia in decision-making (CCAMLR Performance Review Panel, 2017) (Table 9.2).

This section identifies priority tasks for maintaining a low risk of failing to conserve Antarctic ecosystems – satisfying the CAMLRC Fishery Principles (a focus on the krill fishery), achieving the conservation objective in the face of climate change, considering rational use in light of innate ecosystem services and the overarching science needed to refine, revise and update these tasks.

9.6.1 CAMLRC Fishery Principles and the Krill Fishery

Large-scale ecosystem effects of krill fishing are protected by the trigger levels in Conservation Measures of CCAMLR (CMs). For this fishery, the primary question regards what evidence Members of CCAMLR need for them to decide that the krill fishery can move beyond the current trigger levels and by how much. An orderly development of the krill fishery means that the harvest strategy (total catch, its distribution in space and over a year, and the number of years that the fishery would operate in this way) does not increase the risk of failing to meet the requirements of the Fishery Principles. If the catch is small relative to the productivity of krill and is distributed across the whole of the krill population (fishing pressure is low), then the need to reconcile the issues in Section 9.4 (Table 9.3) is less. As local fishing pressures increase, particularly in areas of high predation pressure (Constable et al., 2023a), so too does the need to deal with the outstanding issues and to establish a suitable feedback monitoring system for checking the status of populations and the food web are meeting expectations (the ninth issue for inclusion in Table 9.3) (Constable, 2011).

Methods for assessing biomass at small and large scales are mostly now established, relying on measures from fishing vessels combined with independent surveys (SC-CAMLR, 2023 Annex 6), although work remains on how to use these in assessments of population status and adjusting small-scale catch limits. Productivity of krill is well bounded by existing studies and the current productivity in the yield calculation is at the lower end of the spectrum. For krill, the main issues are with respect to the stock's variability in abundance (recruitment) and its spatial structure (Meyer et al., 2020, SC-CAMLR, 2023 Annex 6) with evidence that the current yield estimate may be up to three times too high (SC-CAMLR, 2022 Annex 9). The other issues are less developed, although the CCAMLR Ecosystem Monitoring Program (https://www.ccamlr.org/en/science/ccamlr-ecosystem-monitoring-program-cemp) is gradually expanding to address the monitoring of krill predators in some locations.

A feedback management procedure (system) is the harvest strategy, the field monitoring program and subsequent analyses, and the decision process (such as by decision rules) to adjust the harvest strategy based on the analyses. The performance of the management procedure is its ability to keep the likelihood to a low level of a specified harvest strategy failing to meet the Fishery Principles. At present, that likelihood is set at 0.1 in the current decision rule. The extent of field and analytical work only needs to be as much as what is needed to make decisions to adjust the harvest strategy in order to maintain the likelihood of failure at or below the agreed level.

Considerable work has been done to facilitate the design of a feedback management procedure that would enable ecosystem checks (from field assessments) and catch adjustments over time (Constable, 2002, Constable, 2011, SC-CAMLR, 2011 Annex 4, 2023 Annex 6, Hill and Cannon, 2013, Klein and Watters, 2020).

TABLE 9.3 Issues remaining on managing the Antarctic krill fishery, relevant questions to be addressed, possible approaches for resolving them in advance of raising the catch limit, and field monitoring required in a feedback management system to check that the issue is not of concern (note that the need for field monitoring of an issue is dependent on the scale of the fishery relative to the abundance of krill in fished areas and the dependence of krill-predators on those areas)

Issues	*Questions*	*Approaches in advance of raising catch limit*	*Field monitoring in feedback management*
Issue 1 Application of the decision rule	Will the decision rule and its assessment be suitable for satisfying the fishery principles once the stock is within the range of long-term variability expected around the target level? And under conditions of climate change? How often should the assessment be updated? Should the median over the whole projection period be the target level, rather than the median expectation at the end?	Evaluate rule under different scenarios of change and levels of stock reduction to test whether the fishery principles are satisfied in the long term.	Krill population status (sufficient regularity to account for variability)
Issue 2 Depletion limit	Will the depletion limit satisfactorily avoid unstable recruitment in the krill population?	Determine the key drivers of recruitment and how recruitment varies as a combination of population size and age/size structure	Recruitment of juveniles to the population (taking account of environmental variability and productivity)
Issue 3 Target escapement	How sensitive are different predators to the effects of fishing? Is the escapement level sufficient for the needs of predators? If predators do decline as a result of prey removal, will they recover in 20–30 years? Could other effects on predators impact their potential for recovery in two to three decades?	Estimate abundances of predator populations and annual consumption of krill. Based on life histories of predators, use models of population dynamics to assess how changes in krill abundance will affect their performance and how fast they would recover should fishing cease.	Status of predator populations (sufficient regularity to account for variability)

Issue 4 Krill mortality function	How should krill mortality be implemented in the yield assessment in order to characterise the predator–prey dynamics of the krill-centric food web?	Estimate possible mortality functions from foraging ecologies of predators, including as food web recalibrates	Predation pressure - consumption of krill by predators (predator abundance and diet) relative to krill abundance
Issue 5 Efficacy of krill-centred rule	Will the fishery be an additional source of mortality as assumed in the current model or will it replace predators in the system, such that predators will decline but the krill population remain stable? If so, is relying only on status and dynamics of krill stocks sufficient for safeguarding predators?	As per issue 1	Status of krill and krill-predator populations
Issue 6 Provision for whale and seal recovery	How will fishing impact the continuing recovery of different whale species and Antarctic fur seals?	As per Issues 1 and 4 but with performance of the predator populations judged against pre-exploitation abundance, not current levels.	Trajectories of recovery of whale and seal populations
Issue 7 Climate change & ocean acidification	How will productivity and recruitment in Antarctic krill be affected by climate change and ocean acidification? How sensitive are different predators to the effects of climate change and will fishing exacerbate those sensitivities?	As per Issues 1 to 4.	Spatial and temporal sampling of indicators relevant to assessing these impacts
Issue 8 Updating spatial overlap	How often will the spatial structure of the fishery need to be updated to maintain protection of the spawning stock and of the important foraging areas for predators as the food web recalibrates to the fishery?	As per Issue 1 combined with spatial modelling of food web trajectories.	Spatial structure of the fishery, krill population and population-level distribution of foraging by krill predators
Issue 9 Food web checks	How will the expectations for krill and predators be checked over the course of the fishery and provide feedbacks for adjusting the management of the fishery?	As per Issue 1 combined with testing different metrics and field programs for assessing status and change in krill and predators, and how inclusion of those metrics could be used.	Structure of food webs, the strength of energy pathways, including the relative importance of non-krill pathways, and the degree to which prey-switching may have occurred.

In order to accommodate a staged approach in resolving the nine issues, it would make sense to be able to raise the trigger level at any time, but only to a level for which existing knowledge, assessment tools and field programs give confidence of not failing the Fishery Principles. A particular challenge will be to help ensure the resilience of Antarctic krill and its energy pathway given that an increased fishery will add pressure to this species already being negatively affected by climate change and ocean acidification.

Simulation testing of management procedures under plausible scenarios in advance of their application can eliminate procedures that have poor performance, avoiding a trial and error approach (Constable, 2002), and can assist in their refinement if they are found unable to fully realise their aims (Klein and Watters, 2020). Perhaps, time limits could be placed on such higher catch levels and their harvest strategies, in case the assurances for doing the field monitoring and assessments cannot be met.

9.6.2 Conservation amidst Climate Change

Members of CCAMLR are pursuing marine protected areas

> *to contribute to sustaining ecosystem structure and function, including in areas outside the MPAs, maintain the ability to adapt in the face of climate change, and reduce the potential for invasion by alien species, as a result of human activity.*
> *(Conservation Measure 91–04 pre-amble, CCAMLR, 2023)*

The Commission decided that these protected areas are needed for (i) maintaining ecosystem viability and integrity in the long term; (ii) protecting key ecosystem processes, habitats and species, establishing scientific reference areas; and (iii) protecting areas vulnerable to human impacts, critical to ecosystem function and/or important to maintain resilience or enable adaptation to the effects of climate change (CCAMLR Conservation Measure 91–4, paragraph 2).

Progress towards a specific representative system has been slow, despite extensive work to elaborate such a system from a scientific perspective since the first workshop in 2005 (Chapter 10). Each proposal has been developed within the context of general ecological domains identified in 2008 (SC-CAMLR, 2008 Annex 4). An added value for these areas is to contribute to maximising resilience in their respective domains by avoiding compounding pressures of climate change by other human activities.

Climate refugia, areas with the best chance for retaining cold- and/or ice-adapted species and functioning food webs, need special identification and protection (Constable, 2022). Based on the results of MEASO, areas to the south of 70°S along with Prydz Bay in the Central Indian Sector are likely to be important climate refugia for the spectrum of species around continental Antarctica (Figure 9.9). The current set of proposed MPAs would provide suitable climate refugia except that Prydz Bay is not well covered (Figure 10.6)

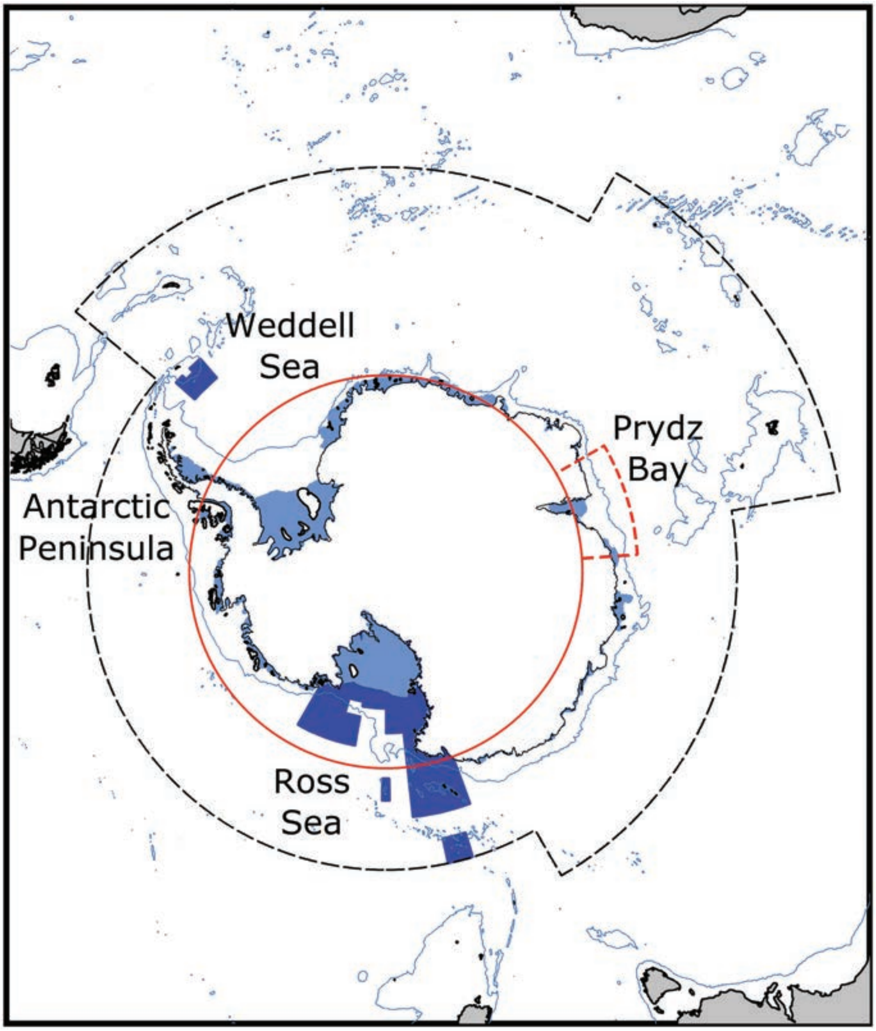

FIGURE 9.9 The Southern Polar Region (Antarctica, subantarctic islands and the Southern Ocean) showing the main southern seas and embayments and the Antarctic Peninsula, the latitude 70°S (red line) along with the additional southern refuge around Prydz Bay (dashed red line), the boundary of the Convention for the Conservation of Antarctic Marine Living Resources (black dashed line; the southern-most part of which is on latitude 60°S, the boundary latitude for the Antarctic treaty). Also shown are ice shelves (light blue), current CCAMLR marine protected areas (dark blue) and the 2000 m isobath (blue lines) (reproduced from Figure 1, Constable, 2022).

9.6.3 Rational Use and Ecosystem Services

Global capture fish production was around 80 million tonnes (Mt) in 2020, with Antarctic fisheries regarded as "relatively minor" and dominated by the krill catch (FAO, 2022). While toothfish and icefish annual catch limits are small and usually taken in full (averaging over ten years – 15,687 t and 791 t, respectively, CCAMLR, 2023), the total annual yield of krill indicated under current Conservation Measures (Table 9.2) could be 8.695 Mt, of which less than 5% is taken at present (CCAMLR Secretariat, 2020). If it was found to comply with the CAMLRC Fishery Principles and taken in full then it would rival anchoveta and become the largest global fishery by tonnage with almost 10% of global fish capture by live weight (FAO, 2022).

Like anchoveta, current trends in the krill market suggest it will be mostly used as meal (79%) rather than as a table food (21%) (Cappell et al., 2022), the latter of which the United Nations Food and Agriculture Organisation uses as a measure of food production from fisheries (FAO, 2022). At present, food-grade krill meal is 29% of meal production with the remainder produced as feed-grade (Cappell et al., 2022). The yield of krill meal from live weight is 14% with krill oil a further 4% as a by-product (Cappell et al., 2022). Cappell et al. (2022) estimate that the combined net operating profit (net value) of the krill fishery at present is approximately US$189 per tonne live weight. They also note that the net value would be less if the full costs of managing the fishery were included.

The main fisheries in the CAMLRC area are certified by the Marine Stewardship Council (https://fisheries.msc.org/en/fisheries/, *Search* – toothfish, icefish, Antarctic krill). For Antarctic krill, fishing activities are only certified for registered companies, rather than the whole fishery, and those certifications are based on compliance with CCAMLR regulations. A number of issues remain over the ecological sustainability of an expanding krill fishery (Section 6.1; CCAMLR Performance Review Panel, 2017). Despite advice from its Scientific Committee, CCAMLR still needs to establish requirements for managing the fishery at its current level, including (i) permanent mechanisms to reduce overlap with krill spawning and nursery areas and foraging areas of predators (Conservation Measure 51–07), (ii) implementing regular small-scale surveys of krill biomass using the now established designs developed by the Scientific Committee (SC-CAMLR, 2023 Annex 12), (iii) eliminating incidental mortality of marine mammals and birds (SC-CAMLR, 2023 Annex 7) and (iv) having scientific observers on every vessel (SC-CAMLR, 2023, CCAMLR, 2023). For the future, it remains to be determined how predators and other aspects of the ecosystem will be satisfactorily monitored for assessing the effects of fishing on food webs.

Rational uses are permitted by CCAMLR provided they meet the requirements of conservation. In the case of fisheries, this also includes adhering to the CAMLRC Fishery Principles. Whether a use is rational needs to be evaluated in the global context (Murphy et al., 2021). What impact might Southern Ocean fisheries have on the conservation of other, especially innate, ecosystem services (Chapters 1 and 11) (Cavanagh et al., 2021, Stoeckl et al., 2024)?

Southern Ocean ecosystem values contribute to genetic diversity, global carbon and nutrient cycles, food production, cultural practices and values, Earth System scientific and technological support, and many others. Ecosystem services of the region are highly valued, most notably related to innate services such as carbon sequestration (Stoeckl et al., 2024). Yet, these services are at increasing risk from climate change (Cavanagh et al., 2021).

Toothfish and icefish fisheries have a negligible role to play in the Earth system. While the krill fishery does not contribute directly to global food production (Nicol and Foster, 2016, FAO, 2022) it may do so in future (Cavanagh et al., 2021). However, the potential magnitude of the krill fishery may negatively impact other values/services.

Over the last decade, concern for the impacts of krill fishing on ecosystem services underpinned by krill has come to the fore, particularly in relation to effects on biogeochemical cycles and carbon sequestration and storage (Cavan et al., 2019, Cavan et al., 2022). Removal of krill combined with food web effects on whales will likely reduce the quantity of iron recycled, thereby impacting annual system productivity including krill (Cavan et al., 2019).

Estimates of the value of sequestering carbon dioxide, known as the social cost of carbon dioxide, enable direct comparisons of the competing global benefits of the krill catch versus carbon sequestration in economic terms. Using the results of Cavan et al. (2022) but replacing the social cost of carbon dioxide with the revised figure of US$185 per tonne CO_2 (Rennert et al., 2022), the value of krill catch as carbon sequestered for longer than 100 years over spring and summer would be approximately US$146 per tonne live weight. If krill moults were included, then this value could potentially increase to around US$259 per tonne live weight. The authors of these calculations have indicated the need for further work but note reasons why the values could be much greater. When compared to the net value of the krill fishery (above), krill have a greater global value per metric ton as carbon sequestrators than as meal and oil from the krill fishery. Further, this net value of the fishery will be even less if it included the full cost of managing the krill fishery borne by CCAMLR Members. Such global and all-encompassing perspectives need to be considered by each Member when deciding whether activities be accepted as rational use, and what would be an appropriate expansion of the krill fishery.

9.6.4 Overarching Priorities for Science

Since the advent of the BIOMASS program over 40 years ago, a number of ambitious, intensive, ecosystem-oriented, international scientific programs have been undertaken in this distant, expensive and difficult operational environment (see Brasier et al., 2019 for review). Nevertheless a large number of topical questions remain unanswered. Technological innovations are paving the way for improved and cheaper research (Newman et al., 2019). Attention needs to be expanded from phytoplankton and krill to the whole food web; there are vast gaps in understanding the ecologies of predator populations and whether the copepod/salp energy pathways are becoming more dominant where krill once swarmed the greatest. Perhaps the contraction of the spawning areas and larval supply of krill to the southern realms (Atkinson et al., 2022) is driven not just by physical forces but by increases in the abundance of small mesopelagic fish preying on krill larvae in the north. Such a possibility is consistent with expected climate change impacts on Southern Ocean food webs (Trebilco et al., 2020).

The MEASO (Constable et al., 2023b) highlights the complexity in projecting ecosystem change because of variation between areas in the relative importance of different energy pathways and different drivers (Figures 9.2, 9.4). It also highlights that models remain to be developed that capture the full suite of properties to assess ecosystem change or to evaluate the relative merits of different approaches to maximise the resilience of these ecosystems. As lags in ecological recalibration amongst taxa increase, the relative importance of different drivers of change on different taxa will inevitably alter, creating less predictability of the future based on what we know and what tools we have available now. That each MEASO area (and the taxa within them) is changing at different velocities makes learning in one area difficult to apply to another without suitably comprehensive field programs; process studies will need to be accompanied by time-series of abundances of taxa that may influence those processes (Constable et al., 2016a).

No single nation can cover alone the breadth of what is required (see MEASO scope and priorities in Constable et al., 2023b, and other specific plans, e.g. Newman et al., 2019, Southern Ocean Task Force, 2021, Meyer et al., 2020). An internationally coordinated, single but federated, end-to-end ecosystem program is needed, with satisfactory sustained decadal investment in developing a coherent ecology of and ecosystem support services for the region. This program needs three interrelated pillars.

First, a regionally coordinated field program amongst nations in areas of common interest with shared laboratory and publication activities will provide opportunities for solving the larger questions and providing sustained time series of species' metrics suitable for tuning ecosystem and other models and enabling assessments of drivers of change, including the relative importance of fisheries and climate change. Such coordination has occurred, such as for the recent estimation of krill biomass (Abe et al., 2023, Krafft et al., 2021, Cox et al., 2022). However, this has only occurred every 20 years since BIOMASS (El-Sayed, 1994), but not for the whole food web. The Southern Ocean Observing System, a joint program of the Scientific Committees on Antarctic Research (SCAR) and on Oceanic Research (SCOR), provides such a structure (Newman et al., 2019). The design of the biological components of the field program needs to be developed (Constable et al., 2016a). The CCAMLR Ecosystem Monitoring Program can provide the foundational work in setting standards and opportunities for collaboration. Data from these programs, including fishery-supported surveys and monitoring for assessments, need to be publicly available in order to advance science in a collaborative and coordinated manner (Van de Putte et al., 2021).

Second, an integrated Southern Ocean ecosystem virtual (modelling) laboratory is needed to provide support for exploring the relative importance and theoretical underpinning of different physical, chemical and biological phenomena causing change in ecosystems, exploring plausible scenarios of the future, reconstructing a pre-industrial ecosystem baseline from which we can compare current and future trajectories, testing management strategies and facilitating the design of field programs. Such a laboratory could also be used for evaluating different modelling approaches, helping integrate and benefit from single/multi-species modelling and helping the development of models to be "right for the right reasons". It could provide a means by which consensus amongst scientists could be developed, particularly in applications where outcomes may be hotly debated, such as in fisheries, conservation and climate change. At the core of such a modelling laboratory is the ability to couple different models (ensembles) at different scales, helping developers focus on parts of the modelling without having to do it all (Melbourne-Thomas et al., 2017, McCormack et al., 2021b). Work of the SCAR/IMBER program Integrating Climate and Ecosystem Dynamics (ICED) (Murphy et al., 2008) could be used as a foundation (Murphy et al., 2012) for achieving this broader remit, with updated requirements for modelling recently reviewed in MEASO (McCormack et al., 2021b). An example of the success of such a laboratory is the Alaska Climate Integrated Modelling (ACLIM) project (Hollowed et al., 2020)

Third, the MEASO (ICED, SCAR, IMBeR) needs to be advanced to routinely assess the status of food webs and trajectories of change for the ecosystem as a whole and to develop suitable metrics for assessing and summarising change, derived from the field programs and the virtual modelling laboratory (Constable et al., 2023b).

9.7 Concluding Remarks

Antarctic and Southern Ocean nations need to be congratulated for ceasing overexploitation in the Southern Ocean, regulating all modern fisheries in the region using the precautionary approach of CCAMLR, and providing for the orderly development of the krill fishery by capping fishing until the CAMLRC Fishery Principles can be assured. As market accreditation judges ecologically sustainable catches of the krill fishery according to a company's compliance with CCAMLR Conservation Measures, the burden is solely on CCAMLR to only raise the caps on krill fisheries, a decision that needs consensus, when it can be confident the risks of failure will not increase. That said, the greatest challenge at present is climate change and the need to maximise the conservation and resilience of Southern Ocean marine ecosystems, particularly cold-adapted and ice-dependent food webs. Protecting important climate-sensitive areas and climate refugia is an important and valuable first step. However, being able to plan conservation and long-term resilience, within which rational use can occur, needs a much greater investment than at present to develop a circum-polar, whole-of-ecosystem knowledge and practical tools that facilitate planning and decision-making. Such investment in science is urgent in this time of a rapidly changing region.

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10

POWER AT THE BOTTOM OF THE WORLD

Emerging Geopolitics in an Exceptional Place

Cassandra Brooks, Tony Press, Evan Bloom, Lyn Goldsworthy, and Jiliang Chen

10.1 Introduction

The Ancient Greeks insisted that a great southern continent must exist, in symmetry with the north. Without it, they said, the Earth would topple over. The Greeks were of course right, as since its discovery, scientists have documented that the Antarctic is vital to the Earth systems. It stores ~90% of the Earth's freshwater, regulates global climate, and drives ocean circulation (Grant et al. 2013, Pertierra et al. 2021)(Figure 1.1). The Antarctic also harbors some of the world's last wildernesses on land (Leihy et al. 2020) and the healthiest marine ecosystems on Earth (Halpern et al. 2015). Being the windiest, driest, iciest, and coldest of the continents, life on and in the waters surrounding Antarctica is superbly adapted to this extreme environment.

It wasn't until the late 1700s that explorers arrived south of the Antarctica Circle driven by exploration, power, and a search for resources. Thus, historically, Antarctica had been protected by its remoteness, with the nearest other land masses being South America 1000 km away across the roughest stretch of water in the world – the Drake Passage; Australia 2500 km away; and South Africa 4000 km away. Antarctica also has extensive sea-ice which, historically, has expanded around the continent every winter (Figure 0.1), acting as a barrier to access, and effectively doubling the size of the continent. During the late 1700s to mid-1900s, explorers found their way south, amid the ice, to claim territory, map the continent, and harvest seal and whale populations. By the 1940s, Antarctica had been divided into territories, with sovereignty claimed over a majority of the continent by seven States (Argentina, Chile, United Kingdom, Norway, Australia, France, and New Zealand). Two States, the United States and USSR, denied the existing claims and reserved their rights to claim any or all of Antarctica. Tensions over claims were, at

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times, extreme, with some States threatening to wage war in and over the continent (e.g., UK Parliament 1952, 1953). Post-World War II, the United States sent thousands of troops to Antarctica to train in extreme environments (e.g., Operation HIGHJUMP).

With the increasing concern that the United States and Soviet Union would extend active Cold War rivalries to Antarctica, something unprecedented happened: the States involved gathered in Washington and agreed, in 1959, to the Antarctic Treaty, setting aside the entire continent and surrounding waters for the sake of international peace and science. Through the Treaty and later associated agreements, the Antarctic Treaty System (ATS) suspends sovereignty and prohibits military operations, mining, and most resource extraction (except for fishing, see below). Celebrated as an extraordinary case combining global diplomacy, environmental protection, and scientifically-based marine resource management (Berkman et al. 2011), the ATS, through its Environmental Protocol, sets aside the Antarctic as a "natural reserve devoted to peace and science".

While arguably the ATS (see Box 10.1) has effectively kept Antarctica as an international space dedicated to peace and science, new geopolitical tensions are emerging reflecting power shifts around the globe. Throughout this chapter, when we refer to "geopolitics" we mean the relationships between space, place, territorial security, and State power. Below, we explore these new geopolitical tensions and whether the ATS is equipped to function effectively given the emerging geopolitical climate, and the global threat of climate change. We investigate the dimensions of science, which simultaneously advances global knowledge, but not without a political edge. We examine new tensions over fishing activities in this last frontier. Finally, climate change is by far the biggest threat to the physical stability of Antarctica and the life that depends on it. Yet, the ATS has been slow to deliver tangible initiatives, such as managing the impacts of climate change in the regulation of fisheries measures, and in establishing comprehensive and representative marine and terrestrial protected areas as biodiversity and climate refugia. We reflect on past diplomatic successes, including the signing of the Antarctic Treaty at the height of the Cold War; the agreement to the Protocol on Environmental Protection to the Antarctic Treaty in 1991; and more recently the adoption of the world's largest marine protected area (MPA) in Antarctica's Ross Sea. We note that these accomplishments inspire hope that despite external political tensions, the Antarctic can continue as a global international exemplar dedicated to peace, science, and conservation.

BOX 10.1 THE ANTARCTIC TREATY SYSTEM

The ATS comprises the 1959 Antarctic Treaty and subsequent related international agreements, institutions, and laws that have arisen since the Treaty came into force in 1961 (Figure 10.1). These include the 1980 Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention), the

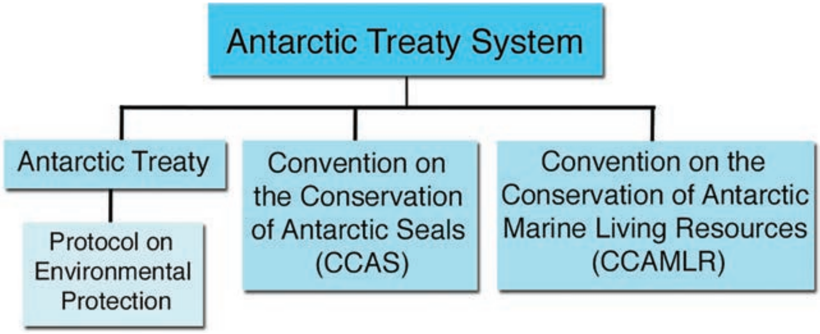

FIGURE 10.1 Main components of the Antarctic Treaty System (ATS). The Antarctic Treaty and its Environmental Protocol, CCAS and CCAMLR are all part of the ATS regime.

1991 Protocol on Environmental Protection to the Antarctic Treaty (Environmental Protocol), which came into force in 1998, and the 1972 Convention for the Conservation of Antarctic Seals (Seals Convention). These agreements are each described below. With the Antarctic Treaty being the foundation, the subsequent agreements comprising key elements of the ATS are all grounded in the Treaty's values of peace and science.

The Antarctic Treaty established, through its Article IX, the Antarctic Treaty Consultative Meeting (ATCM) which meets "...for the purpose of exchanging information, consulting... on matters of common interest pertaining to Antarctica, and formulating for consideration... measures in furtherance of the objectives of the Treaty...". Article IX further identifies a range of matters including the use of Antarctica for peaceful purposes, scientific research, and cooperation, the inspection of facilities, and the "preservation and conservation of living resources in Antarctica." The Treaty provides that "... any State which is a member of the United Nations..." is entitled to accede to the Treaty. Article IX of the Treaty provides that an acceding Party can become an Antarctic Treaty Consultative Party (ATCP) (and, therefore, have the right "vote" in ATCM decision-making) if it "...demonstrates its interest in Antarctica by conducting substantial scientific research there...." From the 12 original signatories to the Antarctic Treaty, which automatically became Consultative Parties, the Antarctic Treaty now has an additional 17 ATCPs (29 total), and an additional 29 Parties that have acceded to the Treaty (58 Parties total). The ATCM currently meets annually and is hosted in turn by ATCPs. All decisions are made based on consensus.

The first international agreement negotiated by the ATCPs after the Treaty came into force was the 1972 Seals Convention. This agreement was preemptive, as no sealing was taking place in the Antarctic at that time. It was also precautionary as it was in part motivated by concern for high latitude seals given the massive slaughter of subantarctic seals that occurred in the late 1700s through 1820s (Hofman 2017, see below). The Convention applies to Antarctic seal species (Southern elephant, *Mirounga leonina;* Southern fur, *Arctocephalus* sp.; crabeater, *Lobodon carcinophaga;* Weddell, *Leptonychotes weddellii;* Ross *Ommataphocav rossii*; and leopard, *Hydrurga leptonyx)* and also sets aside three reserves where no sealing would be allowed (McMurdo Sound, Edisto Inlet, and Signy Island). It also provides for developing precautionary catch limits; however, no State has proposed a harvest, thus the capacity of managing seals has not been tested, and its Parties have not met formally since 1988.

The next agreement was the 1980 CAMLR Convention which was negotiated amid rising concerns over unregulated fishing in the Southern Ocean, especially concern over the potential ecosystem impacts of an expanding krill fishery since Antarctic krill is a keystone species of the Southern Ocean (Miller 2011). There were further concerns that krill fisheries would impact the recovery of Antarctic whale populations which had been decimated in the late 1800s through mid-1900s (Hofman 2017). The CAMLR Convention (Article I.2) applies to the marine living resources, defined as "populations of fin fish, molluscs, crustaceans and all other species of living organisms, including birds" "south of the Antarctic Convergence." Importantly, rather than aligning with the circular boundary of the Antarctic Treaty Area (60°S) (Figure 10.2), the CAMLR Convention Area aligns with the Antarctic Convergence, an ecological boundary that delineates the colder waters of the Southern Ocean (Figure 10.3). CCAMLR's objective, set out in Article II, is "the conservation of Antarctic marine living resources... where 'conservation' includes rational use." The CAMLR Convention requires the use of precautionary and ecosystem-based approaches based on the best available science (CAMLR Convention, Article II). The intention of the ATCPs that negotiated the CAMLR Convention was that its conservation mandate was comprehensive. Unlike regional fisheries agreements of the time, the Convention was not negotiated to ensure the maximum sustainable yield of its fisheries, but rather to ensure the continued health and integrity of marine ecosystems of the Southern Ocean (Press et al. 2019).

The CAMLR Convention establishes three significant institutions: the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR); the Scientific Committee for the Conservation of Antarctic Marine Living Resources (SC-CAMLR); and the CCAMLR Secretariat. CCAMLR meets annually to agree to Conservation Measures that form the legally binding provisions governing the conservation of marine living resources in the Antarctic. SC-CAMLR is a consultative body to the Commission and each CCAMLR Member can appoint a person with suitable scientific qualifications. SC-CAMLR is tasked with providing a broad range of scientific advice to CCAMLR regarding Antarctic marine species populations and ecosystems, measures to ensure their conservation, and programs of scientific research. It also provides advice on catch limits for harvested species. The Secretariat, based in Hobart, Australia, has the role of supporting CCAMLR and SC-CAMLR (and its Working Groups). The Secretariat is not a decision-making body but provides the necessary information, data, and support required by Members to meet, formulate measures relating to the Convention, and monitor compliance with CCAMLR Conservation Measures. CCAMLR currently has 27 Members (26 States plus the European Union), and 10 additional acceding Parties. Decisions are taken during the Commission's meetings by consensus.

A Convention on the Regulation of Antarctic Mineral Resources was also negotiated in 1988 but never entered into force (Jackson 2021). Importantly, there was no mining taking place in Antarctica when the Minerals Convention was being negotiated, but the purpose of the Convention was to put in place a regulatory regime that would manage exploration and mining, and its environmental impacts, if ever mineral activities were to proceed. Against the backdrop of intense opposition to mining by environmental activist groups and non-governmental organizations, the Minerals Convention was abandoned and effectively replaced by the 1991 Protocol on Environmental Protection to the Antarctic Treaty (Jackson 2021). The objective of the Environmental Protocol is "...the comprehensive protection of the Antarctic environment and dependent and associated ecosystems...." It designates Antarctica "... as a natural reserve, devoted to peace and science" (Article 2). The Protocol superseded the "Agreed Measures for the Conservation of Antarctic Flora and Fauna" that were adopted under the Antarctic Treaty in 1964 (Press & Constable 2022). The Protocol sets out a regime to regulate and limit the environmental impacts of all activities in the Antarctic Treaty area and requires prior assessment of all activities (Article 3). Article 7 of the Environmental Protocol prohibits any activity relating to mineral resources, thus instituting an indefinite ban on mining. The Environmental Protocol established the Committee for Environmental Protection (CEP; Article 11). The CEP's role is "...to provide advice and formulate recommendations ... in connection with the implementation of this Protocol for consideration at Antarctic Treaty Consultative Meetings..." (Article 12). The CEP, while a separate body to the ATCM, reports to the ATCM with its advice, including advice on establishing new measures to regulate Antarctic activities. The Environmental Protocol also has 29 Consultative Parties and an additional 13 acceding States (42 total).

A number of other organizations can attend annual meetings of the ATCM and CEP as well as CCAMLR and SC-CAMLR, not as voting members but as observers and invited experts who can contribute to the discussions. Official ATS observers include the Scientific Committee on Antarctic Research (SCAR), which provides independent scientific advice to the ATS, and the Council of

Managers of National Antarctic Programs (COMNAP), which provides operational advice. Active expert organizations include industry groups, such as the Coalition of Legal Toothfish Operators, the Association of Responsible Krill Harvesting Companies, and the International Association of Antarctica Tour Operators; the Antarctic and Southern Ocean Coalition representing more than 15 civil society organizations from across the world; and intergovernmental organizations, such as the International Union for the Conservation of Nature, the United Nations Food and Agricultural Organization, and the Association of the Conservation of Antarctic Petrels and Albatross.

10.2 Antarctic Science: Geopolitical Impacts and Implications

Science and politics are intertwined in Antarctica and have been for more than a half century (Dodds et al. 2017). During World War II, Antarctica was subject to military activities by a number of States, and by the 1950s seven States had advanced territorial claims there (Figure 10.2). Those claims, the potential that the United States and Soviet Union might advance their own claims, and Cold War political tensions, had led to concerns that Antarctica could become an area of international discord (Berkman et al. 2011). The research program of the International Geophysical Year (IGY) of 1957–1958, however, organized by national science academies of major States to promote polar science cooperation, gave rise to the idea that perhaps Antarctica could be demilitarized and brought States together with a common purpose to advance science (Berkman et al. 2011). The result was the Antarctic Treaty signed in Washington in 1959 whereby the original 12 signatories agreed to reserve their position on the territorial claims, to promote international cooperation in scientific investigation, and set aside the continent "for peaceful purposes only." The 12 original signatories are Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, Russian Federation, South Africa, the United States and the United Kingdom.

Without militarization (although militaries can be used for science logistics) and consistent with acceptance of the idea that the main activity in Antarctica is science, the way to establish influence in Antarctica has been by sending scientists and support personnel, and setting up scientific infrastructure and logistics (Bloom 2022). Indeed, for States beyond the original 12 Parties to have a decision-making role as an ATCP, the Treaty provides that a State must engage in science (Box 10.1). The main infrastructure in Antarctica consists of research stations built and operated by national Antarctic programs. There are now more than 80 active research stations operating at least part of the year (Figure 10.2) (COMNAP 2024). Those stations and the activities they support underscore the political aspirations of relevant States (Berkman et al. 2011). Hence, Argentina operates the most stations of any State, placed within its claim in the Antarctic Peninsula. The Russian Federation for

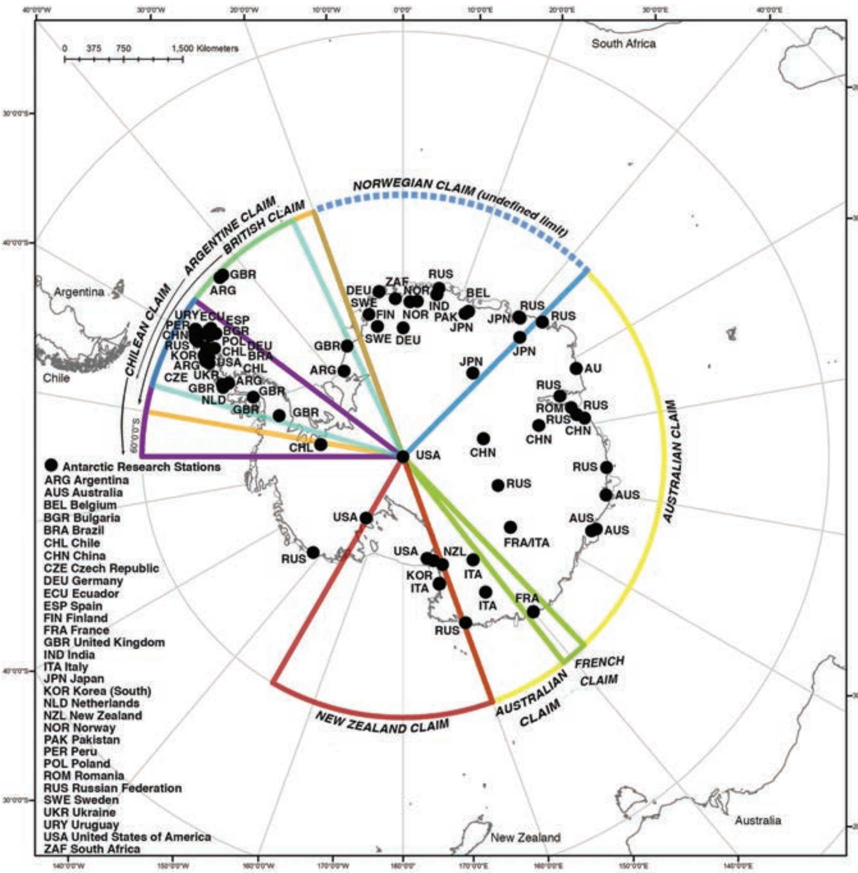

FIGURE 10.2 Historic claims and Antarctic research stations. Historic sovereignty claims in the Antarctic demonstrated by colored wedges (red: New Zealand, yellow: Australia, green: France, blue: Norway with an undefined northern limit, orange: United Kingdom, turquoise: Argentina, purple: Chile). Black circles represent currently operating (seasonal or year-round) Antarctic research stations, labeled according to the State that operates them (infrastructure data from the SCAR Antarctic Digital Database, http://www.add.scar.org; GIS Claim boundaries from Natural Earth; from Brooks 2017).

decades has operated stations strategically placed around the continent in different sectors. The United States operates three year-round stations, including the largest of any State (McMurdo Research Station) and the only station at the geographic South Pole (Amundsen-Scott Station). By placing a station at the South Pole, at the terminus of the pie-shaped claims, the United States declares its presence in all sectors and its ability to operate throughout Antarctica despite the various claims (Elzinga 2011, Klotz 1990).

The presence established via science by States reflects the history of those States in Antarctic exploration, while also indicating the future of Antarctica when economic and political interests may be different from what they are now. Establishing a presence now can secure a place at the table for decisions about governance in the coming decades (Elzinga 2011). Political and territorial interests in Antarctica have had the effect historically of increasing the commitment of States to conduct science there. This is relevant given the remote and unforgiving conditions of operating in Antarctica means that activities are logically difficult and expensive. All of the claimant States, for example, maintain large Antarctic science programs (Hughes & Grant 2017). Indeed, they do this to a significant degree to support their presence and influence for political reasons, even if that isn't how the science programs are necessarily publicly justified. There is a similar phenomenon for Russia and the United States, which seek to raise their profile and pursue security-related policies in the region (Bloom 2022, US Antarctic Policy 2024). China has, for a decade, been steadily increasing its investment in people and facilities in Antarctica as well, clearly following what it perceives as its long-term geopolitical interests, as well as economic interests in a fisheries context (Liu 2019a).

Thus, paradoxically, States competing for influence in Antarctic affairs tend to drive Antarctic science budgets upwards, with attendant benefits for all humankind. This result is one of the enduring achievements of the ATS. Indeed, research in Antarctica has led to major advancements in atmospheric, geological, glaciological, and climate science, as well as oceanography, biology, marine ecology, and evolution (Fogg 1992). Many of these advancements came about through the extensive international scientific collaborations of the International Polar Years (IPY) which occurred in 1882/83, 1932/33, 1957/58 (as the IGY), and 2007/09 (with the next scheduled for 2032/33). In this way, as with the scientific collaboration of the IGY leading to the political collaboration of the Antarctic Treaty, science diplomacy is central to the functioning of the ATS (Berkman et al. 2011).

Science is also key to decision-making in the ATS. As noted above, the Environmental Protocol established the CEP which, while not a scientific committee in a formal sense, involves scientists and provides expertise based on science in its role of advising the ATCPs. SCAR also plays a core role in providing independent scientific advice and is regularly called upon by the CEP and ATCM to compile information on pressing issues (e.g., climate change). The CAMLR Convention demands that decisions are based on the best available science (Article IX), and CCAMLR has further pledged to use the best scientific information from SC-CAMLR (and its subsidiary Working Groups) in its decision-making (CCAMLR Resolution XXVIII 2009).

Despite the centrality of science to the ATS, there are numerous problems with how science is used in the ATS, in particular with how some States may delay or influence scientific processes when it suits various political goals. This problem is particularly acute in the context of CCAMLR. In recent years, CCAMLR has seen political battles play out regularly in SC-CAMLR. For example, SC-CAMLR has been unable to provide consensus scientific advice due to positions taken by a couple of States (notably Russia and China), despite the support from the vast majority of scientists in the room (see, e.g., SC-CAMLR 2022, 2023). Indeed, these States have in many instances asked non-scientists to speak for them in the formal sessions of SC-CAMLR, thus undercutting the effectiveness (and legitimacy) of the proceedings (based on personal observation of the authors).

Further, despite the growing awareness of climate change (globally and within the ATS), the ATCM, and especially CCAMLR, has made very little progress in managing for climate resilience. For example, in CCAMLR, while several proposals have been presented to implement the consideration of climate change risks in fisheries management, to incorporate climate resilience areas in protected areas, and to develop a climate response work plan, so far CCAMLR has been unable to adopt specific climate response actions (Goldsworthy & Brennan 2021, Chavez-Molina et al. 2023). With respect to the ATCM, there has also been a failure to agree on increased protections for Emperor Penguins, which have been proposed directly due to threats from climate change. Consensus agreement on protecting Emperor Penguins has not yet been successful due to China's opposition, in which they advanced a "scientific" rationale which was rejected by most other parties (ATCM 2022, 2023). Here, on an issue where the science seemed relatively clear and robust, there was evidence of politicization rather than the application of reasoned judgment.

In another context, Russia and China in recent years have raised numerous objections to moving ahead with CCAMLR's commitment to establish a network of MPAs, including by preventing progress within SC-CAMLR (e.g., SC-CAMLR 2022, 2023). This has also taken the form of refusing to agree to a research and monitoring plan for the existing Ross Sea region MPA (RSRMPA) and South Orkney Islands Southern Shelf MPA (SOISSMPA). Thus, the research and monitoring plans that were intended to help guide scientific cooperation have instead become part of a political blockade against further work on MPAs (e.g., CCAMLR 2022, 2023).

In addition, since 2021 Russia has expressed "scientific" concerns that no other Party shared, and blocked renewal of an existing Conservation Measure (41-02) for the management of fishing for Patagonian toothfish in waters surrounding South Georgia Island. Russia has used spurious scientific arguments to deny CCAMLR approval for fishing by a Commission Member, in this case, the United Kingdom (CCAMLR 2021, 2022, 2023). The actions by Russia resulted in the United Kingdom unilaterally granting fishing licenses, which, in the view of some States, failed to follow CCAMLR's rules (Arpi & McGee 2022). As a result, the United States refused entry of related toothfish imports. The United Kingdom's action also predictably raised tensions with Argentina because of long-standing disputes over the sovereignty of islands in the region. The merits of the legal and economic issues aside, Russia's claim that science required closure of the fishery lacked substance and undermined cooperation at CCAMLR with potentially serious future consequences (Trathan 2023).

Regardless of the political motivations operating in the background, as a general matter science remains the central organizing principle for common endeavors in Antarctica. This essential element of Antarctic governance sets the region apart from most of the rest of the world giving hope that Antarctica can provide an enduring example of international cooperation. Antarctic institutions can successfully continue this exemplary role only if States take the time and effort to work together with a common purpose and in a spirit of scientific exploration and political compromise.

10.3 Resource Exploitation in the Southern Ocean: Geopolitical Drivers

Early explorers risked their lives traveling to the Antarctic with the aim of not only staking claims but also finding resources presumed to abound in a great southern land. While the harsh environment proved too cold to provide the resources envisioned, explorers did find great abundance of seals, whales, and fish all of which were heavily exploited prior to the negotiation of resource Conventions. These industries, historically and currently, supported overseas markets, but were also used as a means to occupy physical space and exert power.

The first harvesting in the Southern Ocean targeted Antarctic fur seals (*Arctocephalus gazella*) on South Georgia Island, following Captain Cook's reports in 1777 of rich wildlife around the subantarctic islands. As this species was overexploited, activities expanded rapidly to other Antarctic regions and to other species. By 1830, Antarctic fur seals had been hunted to commercial extinction across much of the region, and Southern elephant seals (*Mirounga leonina)* were showing significant signs of decline, and the sealing industry collapsed (Hofman 2017).

A second wave of large-scale commercial hunting was initiated in the early 1900s, targeting whales for blubber, the oil from which helped fuel the industrial revolution. Between 1904 and 1987, an estimated 65 million tonnes of whales (1.15 million animals) were harvested (Trathan & Reid 2009). Some States (e.g., New Zealand and Australia) also used their whaling activities to reinforce territorial claims (Dorsey 2013). Whaling stations (along with exploration, mapping, and science) have also been used to support the territorial claims of the Antarctic claimant States (e.g., Norway's claim; Vigni & Francioni 2017, Apelgren & Brooks 2021). The whale hunt peaked in the 1930s, paused during WWII, and then continued at around 2 million tonnes per year before declining steeply by the early 1960s in response to cheaper petroleum products and the collapse of many whale populations (Hofman 2017).

As whaling declined, commercial fisheries for finfish and Antarctic krill commenced, initiated by the Soviet Union in the late 1960s, partly in response to the development of Exclusive Economic Zones (EEZs) within the Law of the Sea negotiations, which pushed fleets out of national waters (Österblom & Folke 2015). These early fisheries initially focused on marbled rockcod (*Notothenia rossii*) around the South Georgia and Kerguelen Islands, expanding south and to other species as marbled rockcod was depleted (Kock 1992). The Antarctic krill fishery, which was initiated around the same time, was also dominated by the Soviet Union, along with Japan. While the Soviet Union vessels were able to catch and process large amounts of krill (estimated ~500,000 tonnes per season), finding a market was difficult since krill operations generally result in rapid enzymatic breakdown releasing toxic levels of fluorides into its tissue making it unsuitable for human consumption (Ainley & Pauly 2014).

As noted by Constable (see Chapter 9), in the wake of unfettered exploitation, States developed management for marine living resources. First through the establishment of the International Convention for the Regulation of Whaling (ICRW) (1946). Then, through the Antarctic Treaty (1959), followed by the Seals Convention (1972), and the CAMLR Convention (1980) (see Box 10.1). The ICRW was established to address the severe depletion of whale species. The International Whaling Commission (IWC), the regulatory body of the ICRW, enacted a moratorium on commercial whaling in 1985, and an Antarctic whale sanctuary in 1994 (Hofman 2017). The continuation of the Japanese minke whale harvest under the umbrella of "scientific research" (e.g., JARPA II) was eventually halted after Australia initiated a case against Japan in the International Court of Justice and won in 2014 (Mangel 2016, Press 2016). Japan continued whaling under a new special permit (NEWREP-A) from 2015 until 2019, however, the IWC's Scientific Committee continued to scrutinize the research (IWC 2024). In 2019, Japan withdrew from the IWC and ceased whaling in the Antarctic moving its commercial whaling operations into its EEZs and territorial waters (Morishita 2023). Regarding seals, post cessation of sealing in 1964, the fur seal was afforded special protection by the ATCPs. By the early 2000s, both fur and Southern elephant seal populations had increased significantly and were considered fully recovered (Laws 1994, Boyd 1996). Thus, special protection under the Treaty for these seals was discontinued. Finally, the CAMLR Convention introduced an ecosystem-based precautionary approach to the management of human activities in the Southern Ocean, requiring that any harvesting maintained targeted species at stable recruitment levels while also maintaining ecological relationships with dependent and related species and preventing long-term impact on the Antarctic environment (Article II, CAMLR Convention) (see also Constable Chapter 9) (see Figure 10.3 for CAMLR Convention Area boundaries).

When CCAMLR came into force in 1982, Antarctic fisheries could finally be regulated, though not without political and economic influence. By the late 1980s, CCAMLR prohibited the targeted fishing of several species, including marbled rockcod (Constable et al. 2000). CCAMLR sought to regulate krill immediately (given the concerns over fishing this key prey species, see Box 10.1), however, due to the difficulty of consensus-based decision-making, it was only able to agree to a catch limit for krill after the collapse of the Soviet Union, at which point the Soviet Union (and then Japan) ceased obstructing agreement (Brooks & Ainley

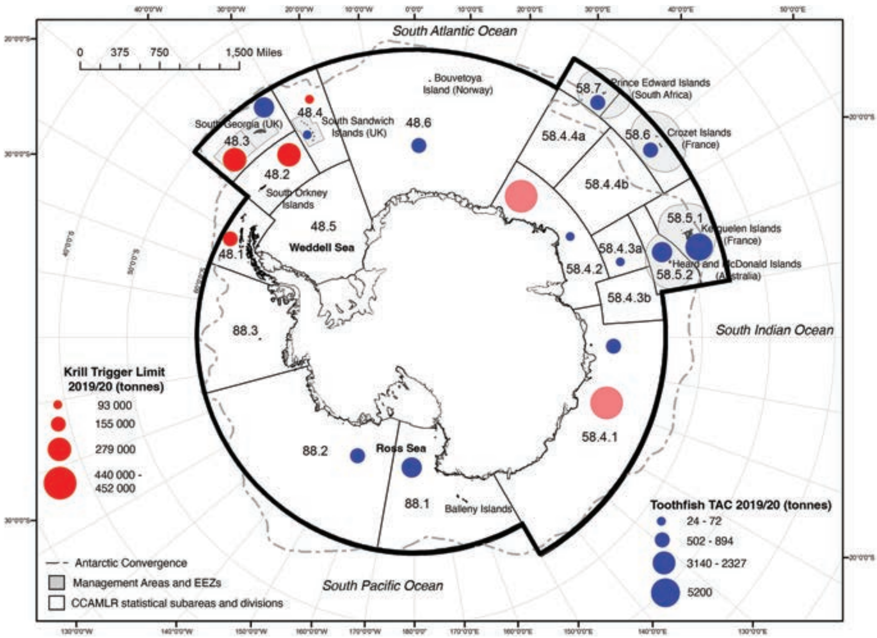

FIGURE 10.3 CCAMLR management areas and allowable catch. Total allowable catch (TAC) for toothfish (blue) and trigger limit for krill (red); circles proportional to respective catch limits (tonnes in 2019/2020), transparency indicates under-utilization. Shaded circles around subantarctic islands reflect delineated Exclusive Economic Zone (EEZ) boundaries generated prior to the signing of CCAMLR. Shaded squares indicate toothfish management area around South Georgia and South Sandwich Islands region, managed by the United Kingdom but contested by Argentina (catch limits and boundaries from www.ccamlr.org). Note that 2019/2020 is used as an example snapshot in time pre-covid-19 pandemic and before the contention of United Kingdom notifications at South Georgia.

2017). Thus, the rapid decline of krill catches aligned with the political collapse of the Soviet Union (see Figure 10.4). Overall catches for krill remained relatively low until the mid-2000s when Norway both developed the new pump technology, which dramatically increased the catch capacity of a single vessel, and created a new market for krill oil as a nutrition supplement for human use (Nicol & Foster 2016).

Currently, krill supports the largest fishery in the Southern Ocean with more than 400,000 tonnes caught per year in recent years of the fishery (Figures 10.3 and 10.4). Norway dominates the krill fishery, with China being the second-largest krill fishing State, commencing its fishing in the late 2000s (Figure 10.4). Aligned with intentions to expand distant water fishing fleets (Liu 2020), China has since invested in the production of two large-scale pump method vessels and signaled

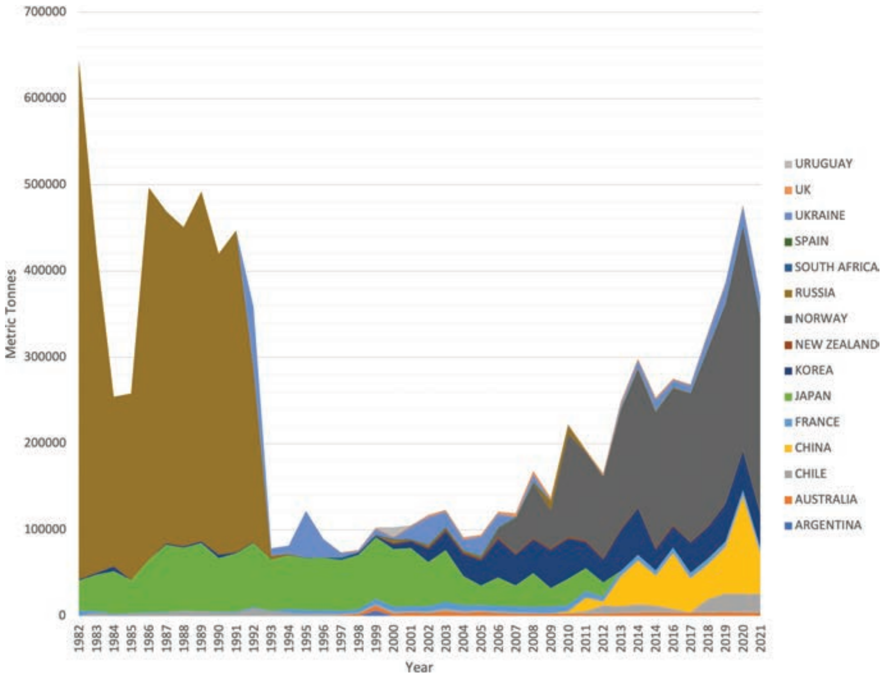

FIGURE 10.4 Total commercial catch of krill, icefish and toothfish (combined) per State in the Convention Area since CCAMLR came into force (1982–2021). Russia includes the current-day Russia and the former USSR. Colors represent the catch per State. Member States with less than 2% of catch for the time period are not labeled (data from CCAMLR Statistical Reports Volumes 2, 12, 15, 25, 34).

its intention to dramatically increase its krill catch. Chile, Korea, and Ukraine are also currently fishing for Antarctic krill (Figure 10.5). Catch has continued to rise in recent years, driven by the omega-3 and fishmeal markets (Nicol & Foster 2016, CCAMLR 2023a). Currently, all commercial fishing for krill occurs in the Scotia Sea region (Area 48). China's attempts to launch a commercial krill fishery in the East Antarctic (Area 58) (see Figure 10.3), perhaps for political as well as economic reasons, have been unsuccessful. The most recent concerns are not about catch limits (which remain at a 620,000 tonne "trigger limit"), but about how locally concentrated the krill catch has become, including that fisheries are potentially over-competing with penguins, seals, and recovering whales (Watters et al. 2020, Trathan et al. 2021, Ryan et al. 2023).

The other main current fishery in the Southern Ocean is for Patagonian and Antarctic toothfishes (*Dissostichus eleginoides* and *D. mawsoni*), which commenced in the mid-1980s in line with the continued global expansion into deeper and more remote waters (Ainley et al. 2012). These species play a key role in the Antarctic marine ecosystems and food webs, both as a top fish predator and key prey species in the Southern Ocean food web (Hanchet et al. 2015). Sold as the lucrative "Chilean sea bass," their high value drove extensive illegal, unregulated, and unreported (IUU) fishing through the 1990s which led to depletion of some populations. Through the rapid development and implementation of new CCAMLR Conservation Measures (e.g., a Catch Documentation Scheme, IUU vessel black-list), IUU fishing was dramatically reduced by the early 2000s (Österblom & Sumaila 2011). Currently, legal fisheries remove about ~15,000 tonnes of toothfish per year from the CCAMLR waters, including around subantarctic islands, some of which are maintained as EEZs (Figure 10.4).

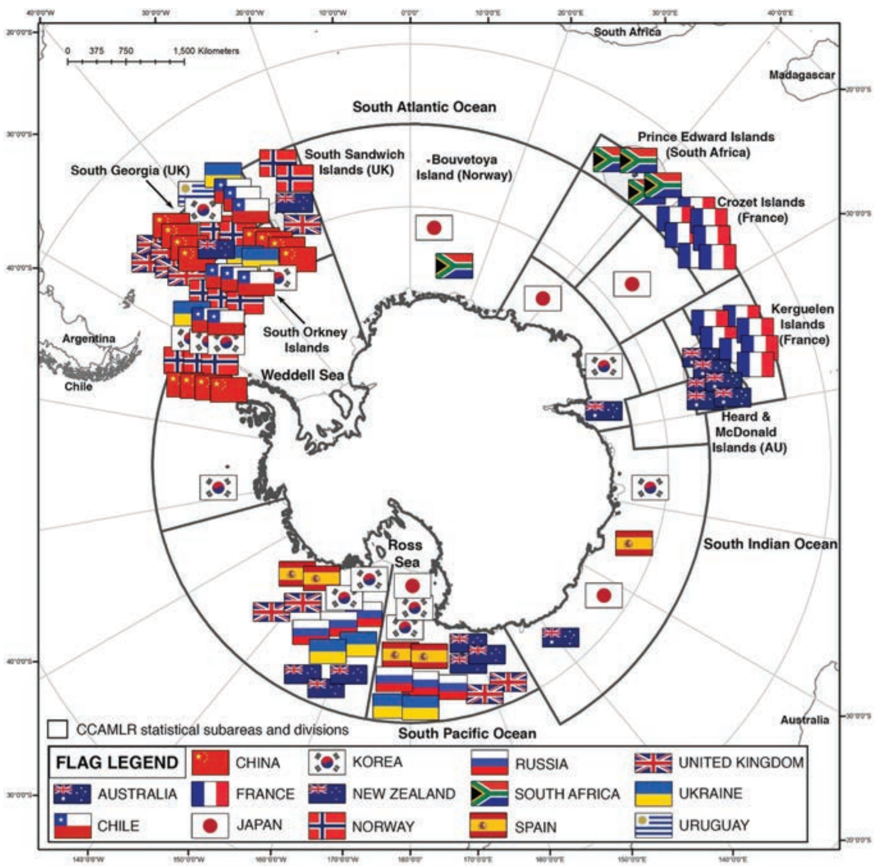

FIGURE 10.5 National fishing operations in the Southern Ocean. Flags of the 14 Member States that notified to fish in the 2019/2020 season. Each flag represents a State vessel that notified for a fishery (e.g., toothfish, krill, or icefish, *Champsocephalus gunnari*) within a CCAMLR subarea or division (CCAMLR boundaries, management areas, notifications, and locations based on data provided through www.ccamlr.org).

The subantarctic EEZ fisheries for toothfish have led to considerable tensions. The CAMLR Convention area includes a number of subantarctic islands that have undisputed sovereignty by Member States and other islands claimed by more than one State. Undisputed territories include the Kerguelen and Crozet Islands (France), Heard Island and McDonald Islands (Australia), and the Prince Edward Islands (South Africa) (Figure 10.3). The "Chairman's Statement" appended to the CAMLR Convention recognizes sovereignty and the rights of these States to exclusive fisheries within the appurtenant EEZs (CCAMLR 1980), including potentially large fisheries for toothfish (Figure 10.3, 10.5). This fact has been mentioned by Russia during CCAMLR meetings, emphasizing unequal access to fishing grounds (Brooks 2013). Further, in the case of those islands where sovereignty is disputed (e.g., South Georgia and the South Sandwich Islands, claimed by both the United Kingdom and Argentina), disagreement at CCAMLR may lead to more direct and contentious complications. Most notable is the example (noted above) of Russia blocking the renewal of the Conservation Measure to fish for toothfish at South Georgia.

Fishing interests in the Southern Ocean are a mixture of economic and political interests. The Antarctic Treaty (Article IV) provides that no new activities in Antarctica can constitute a basis for territorial claims. But the existence of prior territorial claims, the interests of historic and rising superpowers (Russia, United States, China) and the emerging interests of other States (as discussed above) do play out in the maritime geopolitics of the region. For the roughly 14 States that fish annually, they may be using their fishing fleets to project their presence and power. While CCAMLR (which includes many non-fishing States) does its best to institute a precautionary and ecosystem-based approach to management, it must also contend with competing political, economic, and conservation interests. This includes some States ignoring the best available science with regard to climate change policy (as noted above) and MPAs (as noted below) and other States pushing for increased catch limits, without appropriate safeguards for managing environmental change and the needs of krill predators (Trathan 2023). Further, CCAMLR, and the ATS writ large, is not immune to global geopolitical battles; the war in Ukraine has exacerbated tensions in CCAMLR, making decision-making even more difficult in recent years (Liggett et al. 2024).

Beyond marine living resources, economic activity in Antarctica is limited. Tourism is a growing economic activity with potentially increasing environmental impacts, especially given its exponential growth in recent years (Tejedo et al. 2022). Indeed, more than 122,000 tourists visited Antarctica in the 2023/24 season (IAATO 2024). Some ATCPs are involved in bioprospecting (i.e., exploring natural sources for potential product development, including for pharmaceuticals) in the Antarctic, and despite extensive discussion, regulation for these activities has not explicitly been developed (Leary 2020, but see Resolution 7 2005, Resolution 9 2009). Mining remains prohibited indefinitely under Article 7 of the Environmental Protocol. While the media perpetuates false misconceptions that this ban will "expire" in 2048, this is not true; the Environmental Protocol nor any of the Treaties and Conventions under the ATS have an expiration date (Gilbert & Hemmings 2015). Indeed, the ATCPs have continued to state their dedication to keeping the mining prohibition in place through the continued adoption of Resolutions in support of Article 7 (see Resolution 6 2016, Santiago Declaration 2016, Prague Declaration 2019, Paris Declaration 2021, Madrid Declaration, Resolution 3 2023). Thus, unlike the tensions over fishing which creates divisiveness within CCAMLR, the ATCPs remain united, at least in public, in their commitment to ensure resource extraction does not occur on the continent or seafloor.

10.4 Protected Areas: Process & Politics

Protected areas, defined as "a geographic space, recognized, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values" (Dudley 2008, p. 60), are the most prominent tool for conserving biodiversity on land and water (Watson et al. 2014). In light of growing degradation and threats to the environment, international institutions have called for a global network of protected areas (Watson et al. 2014, Gjerde et al. 2016). Most recently, the 2022 Kunming-Montreal Global Biodiversity Framework under the Convention on Biological Diversity calls for the conservation of at least 30% of the land and ocean by 2030 (CBD 2022). Protected areas are an increasingly popular tool for biodiversity conservation because (if well-designed and well-managed) they can lead to increases in biomass, density, and diversity of life (Stolton et al. 2013, Laffoley et al. 2019). To be effective as a conservation tool, protected areas should be representative of the region's biodiversity, including, if possible, all types of identified habitats. Further, depending on the conservation priorities, protected areas can also include vulnerable, rare, and unique species and habitats, as well as areas that provide for species and ecological connectivity and resilience (Stolton et al. 2013, Grorud-Colvert et al. 2021).

Both the ATCM and CCAMLR have the capacity to designate protected areas. Both bodies have committed to do so and have made progress. However, this process, especially in the marine space, has been difficult and increasingly politicized, reflective of the current state in the ATS.

The Environmental Protocol includes provisions for Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs), which could apply to land, freshwater and marine ecosystems (Annex V). The goal of an ASPA is to "protect outstanding environmental, scientific, historic, aesthetic or wilderness values, any combination of those values, or ongoing or planned scientific research" (Environmental Protocol, Annex V 1991). The goal of an ASMA is to "assist in the planning and co-ordination of activities, avoid possible conflicts, improve cooperation between Parties or minimize environmental impacts"

(Environmental Protocol, Annex V 1991). Thus, an ASPA is the more appropriate tool for direct biodiversity conservation under the Environmental Protocol.

Notably, the Environmental Protocol further stipulates (Annex V, Article 3.2) that the ATCPs identify and designate a system of ASPAs to include, *inter alia*, areas kept inviolate from human interference, representative examples of major marine ecosystems, and areas with important or unusual assemblages of species, including major colonies of breeding native birds or mammals. As of 2024, there are 75 ASPAs and 6 ASMAs in force (4 ASPAs and 1 ASMA have been revoked due to changed designation criteria or merging with other ASPAs). However, they are not representative of Antarctic biodiversity, instead being driven largely by proximity to national research stations (Shaw et al. 2014). Of the nine categories of protected area criteria identified by the Environmental Protocol, most have been designated for their representation of important terrestrial ecosystems' or to protect important assemblages of species, particularly breeding colonies of breeding native birds.

Further, the original Antarctic Treaty signatories, especially those with territorial claims, have dominated the designation of ASPAs (Hughes & Grant 2017). While this is likely driven by logistical capacity, and notably ASPAs cannot in any way advance Antarctic claims, they have at times been seen as a tool to demonstrate a connection and management capacity related to adjacent research stations (as noted above) as well as active participation in the ATS (Hughes & Grant 2017). Sporadic efforts have been made to initiate a more systematic and integrated approach to area protection without much success until 2019, when the CEP included this issue in its workplan (CEP 2019).

Designating ASMAs and ASPAs by applying Annex V of the Environmental Protocol is a technical process that until recently has been routine. Though some States may see being a founding proponent of spatial protection or management measures as strengthening its territorial claim or presence (Brady 2017), no legal basis could support such a view. Further, ASPAs generally cover a small area, which limits their strategic significance.

However, the speed of adoption has reduced in the last decade: only nine ASPAs have been designated since 2012, and no new ASMAs have been designated since 2009 (ATS 2024). Further, in 2023, China opposed the inclusion of "prohibited areas" within a proposed new ASPA in Dronning Maud Land, East Antarctica, citing "legal conflict with freedom of scientific investigation … and the inspection rules of the Antarctic Treaty" (ATCM 2023, para 80). The Madrid Protocol Annex V (Article 2 Objectives) expressly permits the designation of prohibited areas within ASPAs. Most other ATCPs noted the particular proposed areas were scientifically justifiable and consistent with scientific freedom and Annex V of the Madrid Protocol (para 78–79, 81–82).

The Chinese proposal for an ASMA, encompassing their Kunlun station at Dome A in 2013, has also generated intensive contestation. China proposed the measure at the ATCM in 2013, but no other parties supported the proposal.

Given that the goal of ASMAs is to manage multiple operators and activities in an area, and that China was the only State operating there (and the only proponent on the ASMA), other ATCPs did not see the need to designate an ASMA at Dome A. Besides the legal contestation, concerns over a rising power's expansion on the continent may have also cast a shadow on the discussion (Liu 2019b). Facing strong opposition at the CEP in 2013, China maintained the informal discussion on this issue for six years with little participation from other ATCPs. The proposal, reframed by China as a Code of Conduct in 2017, still could not get sufficient support from other Parties, and the discussion ended at the CEP in 2019. Some Chinese advisors have suggested that China should re-table the proposal (Jiang & Tang 2023).

Within the marine realm, CCAMLR is responsible for the conservation of Antarctic marine ecosystems within the Convention Area, and Article IX of the Convention provides the legal basis for CCAMLR to establish protected areas. In 2002, after the goal set at the World Summit for Sustainable Development towards a global network of MPAs (United Nations 2002), CCAMLR agreed to work towards this goal in the Southern Ocean. After an extensive bioregionalization process carried out by SC-CAMLR, CCAMLR Members began developing MPA proposals in priority areas, guided by nine MPA planning domains (Figure 10.6) (Brooks et al. 2020a). CCAMLR currently has two adopted MPAs and four proposals under negotiation (Figure 10.6). Extensive scientific effort has supported this process, both at the circumpolar scale (e.g., Grant et al. 2006, SC-CAMLR 2007) as well as regional conservation planning by MPA proponent countries towards developing specific proposals (e.g., Ainley et al. 2010, Teschke et al. 2020). In addition, non-governmental organizations, especially those part of the Antarctic and Southern Ocean Coalition have led a widespread international public conservation campaign (see, e.g., ASOC 2024).

The first CCAMLR MPA, the SOISSMPA, was proposed by the United Kingdom and adopted at the CCAMLR annual meeting in 2009 (through CCAMLR Conservation Measure 91-03). The MPA covers ~94,000 km^2 and is fully protected (e.g., no-take) (Figure 10.6). This MPA was adopted relatively swiftly (i.e., over the course of one meeting). Its swift adoption was likely because it did not interfere with any current or potential fishing operations, was further modified to accommodate a potential Russia crab fishery (which never developed), and came into existence before CCAMLR's Conservation 91-04 (adopted in 2011) which outlines requirements for establishing MPAs (Brooks 2013).

The second CCAMLR MPA to be adopted was the RSRMPA in 2016, a global priority area called *The Last Ocean* due to its remarkable conservation value (Weller 2013, Young 2012). This MPA was grounded in more than a decade of scientific effort, unprecedented high-level diplomacy, and extensive public engagement (Brooks & Weller 2025). The United States and New Zealand led the proposal, which had the core objective to protect the structure and function of the Ross Sea ecosystem, and was agreed to be based on the best available science by

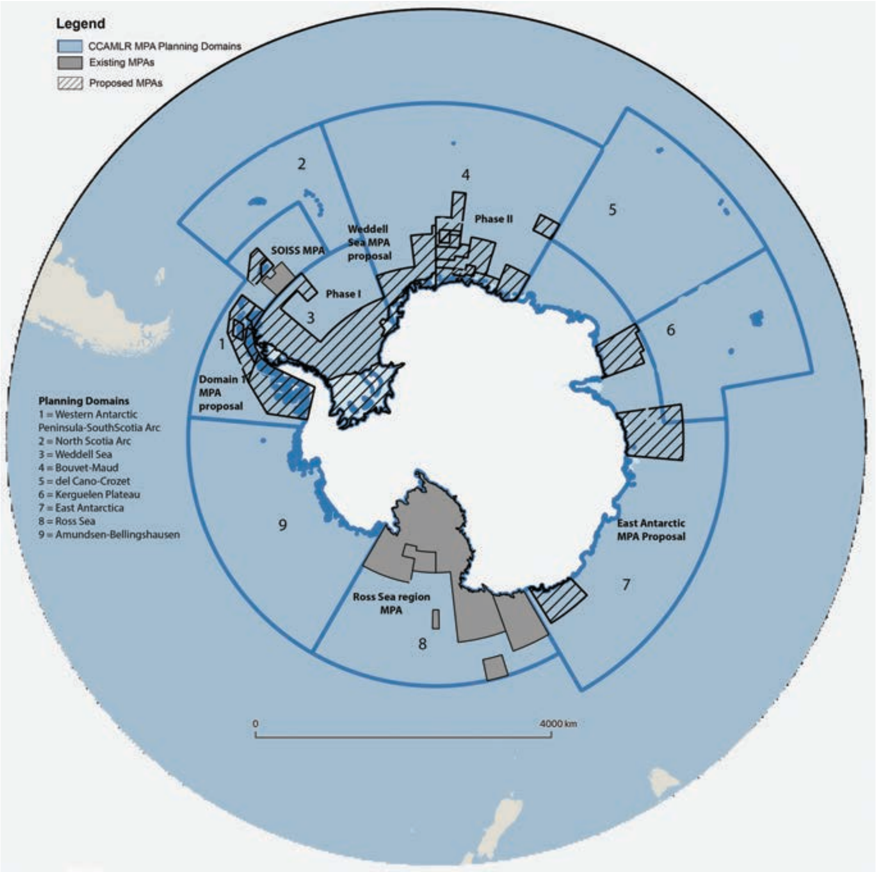

FIGURE 10.6 Network of CCAMLR MPAs and planning domains, showing changes in proposals over time. Gray areas represent adopted MPAs, hashed regions are current MPA proposals under negotiation at CCAMLR (at time of writing). CCAMLR boundaries, planning domains and adopted MPAs based on CCAMLR data from www.ccamlr.org; MPA proposal boundaries provided by proponents.

SC-CAMLR in 2011 (SC-CAMLR 2011). Significant efforts, and compromises, were made to find agreement, including the addition of a Special Research Zone and a Krill Fishing Zone (both allowing some fishing) (Figure 10.6). Reaching consensus demanded diplomacy at the highest level, including discussions between President Obama and President Xi (Tang 2017), unprecedented in polar diplomacy. After five years of intensive negotiations, the RSRMPA was adopted in 2016, upon agreement of a 35-year fixed term for most of the MPA and a 30-year duration for its Special Research Zone (Brooks et al. 2020a). China and Russia were the last two countries to reverse their positions and join consensus. In 2024, the RSRMPA remains the world's largest MPA, covering over 2 million km^2 of area including a 1.6 million km^2 "no-take" zone (including areas covered by the Ross Ice Shelf) (MCI 2024).

A proposal for the East Antarctic, led by Australia and France, was also first submitted to SC-CAMLR in 2011. This proposal, developed as a network of seven multi-use MPAs to protect the core and important ecosystems, biodiversity and habitats, was also endorsed by SC-CAMLR to be based on the best available science (SC-CAMLR 2011). Over the many years of negotiation, the proposal has gone through many compromises as proponents sought to accommodate concerns of other CCAMLR Members. The network of seven was reduced to four, then three MPAs (Figure 10.6) and an expiration date was added (Brooks et al. 2020a). Zoning was added in an attempt to clarify the proposal's multi-use aspect. The eastern section in the D'Urville Sea is zoned as no-take for krill fishing (to protect penguins in the region suffering from climate change impacts) while deep embayments (less than 750m) are proposed as no-take for toothfish (CCAMLR 2017). While the MPA has still not been adopted, it is currently co-sponsored by 18 of the 27 CCAMLR Members (Australia, European Union and its Member States – Belgium, France, Germany, Italy, Netherlands, Poland, Spain, Sweden – India, New Zealand, Norway, Republic of Korea, Ukraine, United Kingdom, United States, Uruguay), showing the widespread support for the MPA (CCAMLR 2023b).

A proposal for the Weddell Sea (Domains 3 and 4) has also been developed, led originally by Germany, but now co-sponsored by 19 Member States (those listed above plus Chile) (CCAMLR 2023b). This proposal, which first came under negotiation in 2016, originally spanned the entirety of the Weddell Gyre (Figure 10.6) and was designed to protect representative ecosystems, vulnerable and unique species and habitats, and to provide scientific reference and climate refugia areas (Teschke et al. 2021). The proposal was considered by SC-CAMLR to be based on "the best science currently available (SC-CAMLR 2016) but not stated as 'the best available science,' a subtle but important distinction in language since only proposals endorsed as the best available science will move to negotiation by CCAMLR. This language came largely from some Members, including Norway, suggesting the Weddell Sea MPA proposal needed further scientific consideration. While not initially opposing German leadership on a Weddell Sea MPA (2012–2015), Norway offered extensive criticism between 2016 and 2018 (CCAMLR 2016, 2017, 2018), potentially due to renewed national interests in Antarctica (e.g., in 2015 Norway published its first dedicated Norwegian Antarctic Strategy) and that the eastern part of the Weddell Sea MPA proposal overlapped with their historic territorial claim (Apelgren & Brooks 2021). In 2019, the Weddell Sea proposal was re-submitted, confined to the area west of the prime meridian and Norway became a co-proponent (Apelgren & Brooks 2021). The western Weddell Sea MPA proposal, now called Phase 1 (Figure 10.6), remains under negotiation at CCAMLR. Consensus has not been achieved despite the extensive science-based process followed by Germany, suggesting the need for higher diplomatic engagement (Teschke et al. 2021). Norway is currently leading the development of the Phase II proposal for the eastern region, which was presented to CCAMLR's annual meeting in 2023. This proposal, which (at the time of writing) Norway was the only proponent of, remains under negotiation at CCAMLR (CCAMLR 2023b).

In 2018, Argentina and Chile submitted an MPA proposal in the western Antarctic Peninsula (Domain 1) for consideration of SC-CAMLR and CCAMLR with the objectives, among others, of protecting representative habitats, important ecosystem processes and areas (Figure 10.6) (CCAMLR 2018). This region is significant because it harbors the majority of Antarctic krill and vast populations of penguins, seals, and whales (which in turn feed on krill). However, it is also the region of Antarctica most impacted by human activities (including research, and fishing) and environmental change (Hogg et al. 2020). This proposal has also undergone many years of revisions and updates, including revised delineations of a general protection zone (no-take) and krill fisheries zone (which accommodates current krill fishing operations) (ASOC 2023). Despite following a transparent, inclusive, and science-based process (Sylvester & Brooks 2020), this proposal has not yet been endorsed by SC-CAMLR nor adopted by CCAMLR (CCAMLR 2023b).

Despite CCAMLR committing to a network of Southern Ocean MPAs, and despite the extensive efforts of the majority of CCAMLR Member States

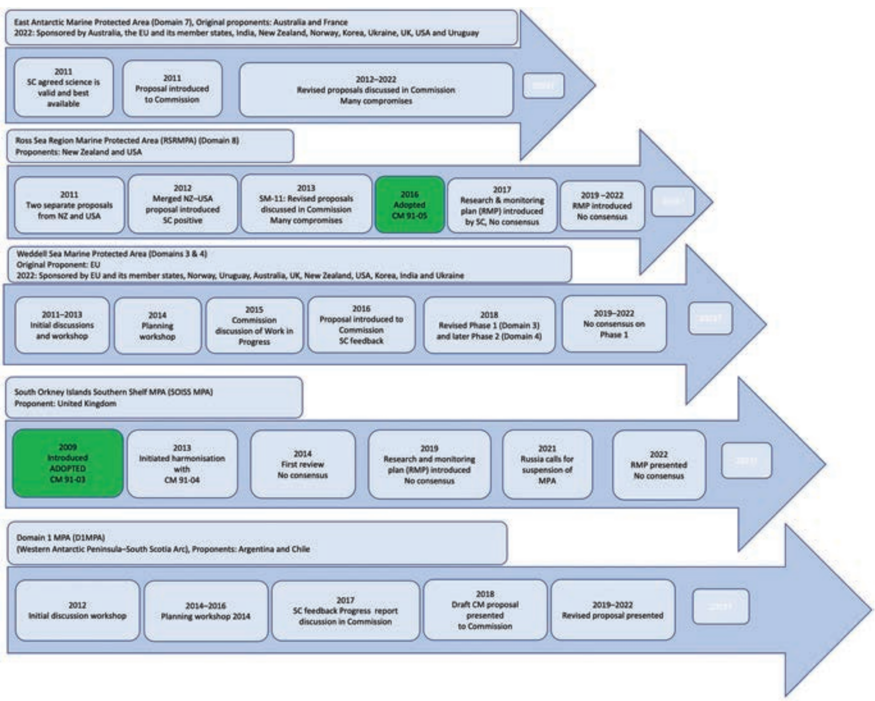

FIGURE 10.7 Timeline for adopted and proposed CCAMLR MPAs. Timeline does not include the Weddell Sea Phase 2 MPA proposal, which only came under negotiation in October 2023. Data from CCAMLR annual meeting reports 2011–2022.

(Figure 10.7), CCAMLR has not yet been able to adopt additional MPAs. China and Russia remain the most vocal opponents of the East Antarctic, Weddell Sea (Phase 1), and Domain 1 MPA proposals. This includes both being vocal during CCAMLR annual meetings and submitting extensive papers to the annual meetings of SC-CAMLR and CCAMLR outlining arguments against the MPAs, both individually and generally (see e.g., CCAMLR 2021, 2022, 2023). Russia at times submits the same papers year after year, showing persistence, and perhaps frustration that some of its concerns are not being addressed (Brooks et al. 2020a). These papers include: requests to abolish the SOISS MPA since it came before Conservation Measure 91–04; a need to evaluate all resource potential before an MPA is considered in the Weddell Sea; statements that no MPAs are needed due to a lack of threats; and accusations that MPAs are based on political rather than ecological boundaries (CCAMLR Meeting Reports, List of Documents 2012–2023). China's first paper submitted to CCAMLR was in 2018, focused on critical ideas around CCAMLR research and monitoring plans, a topic that has become increasingly fraught with tensions (CCAMLR 2018).

While research and monitoring in CCAMLR MPAs should in principle be the responsibility of all Member States, the onus has been placed on the original proponents, with China and Russia criticizing their efforts as insufficient. For example, as noted above, the United Kingdom developed and submitted a research and monitoring plan for the SOISS MPA, but Russia in particular has blocked its adoption, suggesting the MPA should be abolished (see, e.g., CCAMLR 2022). In the case of the Ross Sea, soon after the MPA came into force, the CCAMLR science community developed a Research and Monitoring Plan through an international workshop in which many Member States' scientists attended (including Russia and China) (Dunn et al. 2017). In line with the provisions of Conservation Measure 91–05 (para 14) the Research and Monitoring Plan was introduced to SC-CAMLR and CCAMLR in 2017. The plan was endorsed by SC-CAMLR (SC-CAMLR 2017) but has not yet been agreed to by CCAMLR and has come under increasing scrutiny by Russia and China, with both Member States submitting multiple papers criticizing the Research and Monitoring Plan (CCAMLR 2023b). This criticism has extended beyond the Ross Sea to other MPA proposals, with both of these States suggesting that until the issue of Research and Monitoring Plans is resolved, further MPAs will not be agreed to (CCAMLR 2023b). Thus, not only are the proposals on the tables stalled but also initial work for other Domains (e.g., 5 and 9) has largely not progressed.

With the territorial claims suspended rather than resolved, the scale and location of spatial management proposals can trigger geopolitical concerns (Roura 2023). On land, the Chinese proposal on the Dome A ASMA covers 19,764 km² of area. It would be the second-largest ASMA on the continent if it had been designated. At the same time, the size of current CCAMLR MPA proposals is far above the IUCN's standard of "very large MPA." The sheer size of the area for protection makes those proposals a greater trial and potentially fraught with competing values and geopolitical visions (Dodds & Brooks 2018). Further, spatial management proposals can trigger geopolitical concerns because of their spatial and temporal scale. Notably, CCAMLR MPA boundaries do largely align, or fall within, historical territorial claims of original proponent States (Brooks & Ainley 2017). Some countries (e.g., Russia) have accused MPAs of being politically motivated and of boundaries being based on political rather than ecological boundaries (Brooks 2019). Yet, as noted above in the Antarctic Science section, and as is the case with ASPAs, States will make conservation proposals in areas where they have diplomatic interests and support, and where they have existing science programs that can provide data to underpin an MPA proposal. While an MPA might align with a State's national interests (e.g., many CCAMLR Members have domestic MPA initiatives), it cannot effectively advance territorial or other geopolitical interests because the rules related to spatial management in the ATS cannot establish any exclusive rights for any State. Nonetheless, the geopolitical concerns seem still present despite those institutional safeguards.

10.5 Looking to the Future

The tensions around MPAs in CCAMLR reflect the broader political tensions in the ATS; yet the impact of global biodiversity decline and climate change has become increasingly evident with continued urgent calls for protection of biodiversity and emphasis on the importance of Antarctica. Recent scientific reports have emphasized the role of the Antarctic in understanding the science of global anthropogenic climate change and its role in the maintenance of the Earth systems (IPCC 2019, 2022, Chown et al. 2022). Further, global discussions on managing marine biodiversity in areas beyond national jurisdiction have illustrated the importance of large-scale MPAs in ensuring ocean health (e.g., United Nations 2022). As noted above, the Global Biodiversity Framework calls for protecting 30% of the world's marine and terrestrial areas by 2030. Currently, the CAMLR Convention Area is ~12% encompassed in protected areas (half of these falling within national EEZs and less than 5% being fully protected) (Brooks et al. 2020b), and the ice-free regions of the Treaty Area are only ~1.5% protected (Shaw et al. 2014). It is unclear if ATCPs and CCAMLR will meet global targets given how increasingly political and contentious the process has become, especially within CCAMLR.

In June 2023, CCAMLR held a special unprecedented intersessional meeting dedicated to developing a roadmap towards progressing MPA proposals. The meeting did not attain its objectives and Russia in particular proposed the elimination of the core elements of Conservation Measure 91–04 (CCAMLR IM 2023) related to the establishment of MPAs. Many CCAMLR Members supported the adoption of a non-binding Resolution that would provide a roadmap for future work and voice commitment to MPAs. But the Resolution was downgraded to a Declaration, then a Communique. The original document became so diluted, with Russia and China only agreeing to language around supporting the CAMLR

Convention and managing marine living resources (removing any language around MPAs, protection, or even ecosystems), that negotiations of the document ceased (CCAMLR IM 2023). Many CCAMLR Member States made closing statements voicing disappointment at the lack of progress during the special meeting (CCAMLR IM 2023).

CCAMLR and the ATCM have historically had a mandate to act as decision-making bodies where Members must balance their national interests with international diplomacy. While it is clear that supporting protection aligns with some States' national goals, it does not align with those of others, most notably China and Russia.

While China seems comfortable to accept broad conservation frameworks, it is actively opposing concrete conservation initiatives (e.g., new MPAs, protecting Emperor Penguins) (CCAMLR 2023b, ATCM 2023). China has also clearly expressed its global ambitions to be an active and major player in the utilization of ocean resources and, within CCAMLR, to expand its Antarctic krill fishing activities (Liu 2019a). Consistent with this global approach, China has questioned the necessity for MPAs in CCAMLR, arguing that the area is already afforded strong protection and that rational use – interpreted as a right to fish, should not be impeded (Jacquet et al. 2016, Brooks et al. 2020a). This too aligns with China's questioning of the necessity to protect Emperor Penguins, despite compelling scientific evidence, as protection could be interpreted as leading to restrictions in activities (ATCM 2023). China is effectively attempting to re-litigate CCAMLR's commitment to MPAs, against the wishes of the vast majority of its Members, and perhaps even challenging the foundations of the ATS's environmental protection more broadly.

Russia has a long history of taking strong positions that promote its fishing and other interests. The Russian fisheries agency, which leads its CCAMLR delegation, has historically been opposed to MPAs, although Russia did ultimately agree to the SOISS and Ross Sea region MPAs (Brooks et al. 2020a). The Russian delegation has taken positions in SC-CAMLR that seem more driven by politics and other considerations and has protected Russian vessels from sanctions, such as *the Palmer,* where there was convincing evidence of illegal activity (fishing in a closed area) (CCAMLR 2020, 2021, Bloom 2022). Against this background, it is hard to know whether animosity among CCAMLR Members and the ATCPs as a result of Russia's further invasion of Ukraine in 2022 can explain recent Russian intransigence in CCAMLR and the ATCM. However, it is quite clear that the Ukraine conflict has made working with Russia even more difficult. For example, to the extent that Russia joining in consensus on new MPAs can require concessions or increased flexibility by Russia, it is hard to predict Russia changing its mind until the Ukraine conflict has abated. That may be particularly the case while Ukraine chairs the Commission, which it will do until the end of October 2024.

Both the ATCM and CCAMLR have had difficulty in progressing binding Measures in recent years, in large part due to challenges in bringing Russia and

China to consensus. Yet, with the rising importance of Antarctica as a result of the climate crisis among other reasons, there is pressure on all Parties to achieve policy objectives under ATS. CCAMLR Members need to find a way to recommit themselves to the priority given to conservation under Article II, building on the primacy of science through promoting the work of its scientists, and progressing on its commitment to establish a network of MPAs. In the ATCM, parties can give great attention to finding ways to promote climate science, improve species and area protection efforts and meet the need for greater regulation of tourism. Parties must meet the coming environmental challenges head-on, finding new diplomatic levers of influence and being ready for political windows of opportunity. In particular, they need to work harder to achieve the consensus that the ATS requires, which may mean putting additional diplomatic effort into Antarctic diplomacy, not just at annual ATS meetings but also intersessionally and at more senior levels.

While the current tensions create a temporary impasse, it is important to remember that the ATS has endured, with foundational principles of peace and science, and has seen many great achievements. These include a mining ban, designation of the continent as a natural reserve, sustainable management of fisheries (including combating IUU and reducing seabird bycatch), and designation of the world's largest MPA. These examples show that international diplomacy can lead to unity as all of these successes have been achieved through consensus. Further, there is precedent in the ATS of embracing political windows of opportunity and reaching remarkable agreements. The Antarctic Treaty itself was signed at the height of the Cold War, against all odds, yet crisis and aligned incentives of preventing conflict in Antarctica led to a political breakthrough. Given the current unprecedented biodiversity and climate crises, and the Antarctic's role particularly in the latter, CCAMLR Member States and ATCPs have an opportunity, and responsibility, to act and to ensure Antarctica remains a global exemplar dedicated to peace, science, and environmental protection.

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11

CULTURAL CONNECTIONS WITH ANTARCTICA AND THE SOUTHERN OCEAN

Hanne Nielsen, Elizabeth Leane, Carolyn Philpott, Adele Jackson, and Maria Ximena Senatore

Introduction: Imagining Antarctica

Antarctica and the Southern Ocean have a rich human history of imagination, exploration, exploitation, and admiration. Ancient Greek philosophers conceived of a great southern landmass before Antarctica was ever sighted (see, e.g., Stallard, 2016). Imagined encounters come prior to any human interactions with the far south and continue to be the main route through which humans engage with Antarctica. Although most people will never visit the region, it has captured the imaginations of artists, musicians, and storytellers for centuries (Manhire, 2004; Andrews, 2007; Leane, 2012; MEASO, 2020). For those who live on the shores of the Southern Ocean, including the Yaghan people of Tierra del Fuego and the Palawa people of Lutruwita/Tasmania, it has a constant presence – in the weather and the wildlife, as a food source, and as a connector between the islands on the southern rim of the world. Oral histories connect Indigenous people to the far south, with the southern canoe voyage narrative of Polynesian Hui Te Rangiora (also Ui-te-Rangiora) being but one example (Wehi et al., 2022). Works of art and literature, through their ability to engage our emotions and challenge our presumptions, can inspire new ways of thinking about the Antarctic region (Roberts et al., 2021, p.6). Therefore, when we talk about Antarctica, the conversation should not be limited to what physically lies in the Antarctic region – the culturally mediated *idea* of Antarctica plays an important role in shaping how we perceive the far south.

This chapter draws out cultural connections with the far south to ask how and why Antarctica matters to people back home. Taking "cultural connections" to encompass human conceptions of and relationships with the far south, this chapter traverses cultural representations of the Southern Ocean and Antarctica on a range of scales, and across a variety of media, including music, literature, and fine arts.

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Subsections on these media highlight the key themes that have emerged at various times and use case studies to demonstrate how a remote region has been brought to life back home through the arts. This chapter then uses objects located in the far south to highlight questions of heritage and what is valued and protected. It also considers the experiences of tourists – many of whom are drawn to the region by the stories of past human endeavor – and the role that interpretation plays in an Antarctic tour expedition. This representation of place is further examined in an overview of advertising materials that use the region to sell products and services that often have a conceptual, rather than tangible, link with the Antarctic. Finally, this chapter examines local Antarctic connections by introducing the Antarctic gateway cities and providing an overview of how their inhabitants imagine and experience the region to the south. Together, these examples of cultural connections with Antarctica and the Southern Ocean highlight the importance of the region to a range of communities back home.

Accessing Antarctica

Antarctica's cultural significance extends well before humans first began spending long periods in and around the continent, as the Māori, Yaghan, and Greek examples above indicate. However, since humans first headed south, the cultural representation of Antarctica – and the culture of temporary communities living in or near Antarctica – has been strongly influenced by the people who have visited the region. Antarctica is of course a difficult place to access, thanks to its inhospitable terrain and the turbulent waters of the Southern Ocean that surround the continent. During the 1800s, the sub-Antarctic region was the destination of sealers, heading south to harvest the pelts of Antarctic fur seals. Commercial drivers continued to play an important role in the exploration of the region until the 1930s, with whaling stations operational in the early decades of the 1900s (Basberg and Hacquebord, 2023). The interior of the continent was first explored during the so-called "Heroic Era" of Antarctic exploration (1895–1922), which saw expeditions map coastlines and push ever further inland to reach the geographic and magnetic South Poles. International cooperation around the International Geophysical Year (IGY, 1957–1958) saw the establishment of a number of scientific stations in the Antarctic. These activities prefigured the signing of the 1959 Antarctic Treaty, which put territorial claims into abeyance enshrined scientific investigation and cooperation as the key human activity in the region, and prohibited military activity, except for logistical support Today, scientists and support staff are taken south by national Antarctic programs. Each summer around 5000 personnel work in Antarctica, with 1000 staying over the winter. Spaces on stations and on vessels are limited and often determined by competitive grant schemes.

Although far more people began going to Antarctica after the IGY than ever before, access to Antarctica was largely confined to men, with women only allowed in significant numbers towards the end of the 20th century. Lize-Marié van der Watt and

Sandra Swart explain this largely homosocial environment meant that "Antarctica was the last continent, the last locality, where fantasies of white masculinities could be played out" (2016, p. 146). Moreover, while women now regularly travel to the Antarctic as scientists and support personnel, barriers remain. Several recent reports have documented widespread sexual harassment both in Antarctic communities and in the sector more broadly (Nash, 2022; National Science Foundation, 2023; Russell, 2023). The gendered nature of the continent's history continues to be reflected in the images of Antarctica that circulate in popular culture, often featuring heroic (white male) figures battling the elements. However, as this chapter shows, increasingly artists and writers are using their works to challenge rather than reinforce the stereotype of the continent as the natural domain of white men.

For artists, writers, and musicians themselves, however, access to the continent can also be hard. Several national Antarctic programs have run arts residencies, offering the opportunity for creative professionals to visit stations or accompany science teams on fieldwork missions (Jackson, 2019). For example, the US, Australian, and New Zealand programs have all run artists' and writers' residencies, in some cases for several decades. However, there are limits on the number of people who can access Antarctica in this way, and the closure of the high-profile British and Argentinian programs, due to organisational and financial changes, has curtailed opportunities further. Another access option for artists in recent years has been tourism. Cruise vessels carry both invited resident artists (such as Ken Done and Zaria Forman) and artists who happen to be tourists (such as Jenni Diski, Spencer Tunick, and Pamela Fairburn). There are also cases where entire vessels have been chartered for artistic purposes, such as the Antarctic Biennale (2017) or Metallica's "Freeze 'Em All" concert at Carlini Station (2013).

With greater numbers of people accessing the continent, we might expect to see a greater range of artistic and cultural responses emerging in the coming years. The examples of music, literature, and art examined in the following sections touch on all of these routes southwards. These are not exhaustive – rather, they highlight some key themes associated with how people have interpreted Antarctica through the arts. As we will show, early perceptions of the region do not disappear but are layered over and sometimes transformed by new ones. Some of the common framings that emerge both in artworks and other forms of popular culture are Antarctica as a place for heroes; an extreme environment to be conquered; the epitome of the sublime; a place for science; and a fragile continent in need of protection. As the following section demonstrates, these and other frames emerge in relation to music, literature, and art.

From Antarctica to the World: Fine Art, Music, and Literature

Fine Arts

Since the first documented crossing of the Antarctic Circle in 1773 (during Captain James Cook's second Pacific voyage), when William Hodges' paintings provided the first glimpses into the icy world (Andrews, 2007), the visual arts have

FIGURE 11.1 Standish Backus. 1956. Severing the Tow Lines. 88–186-BA. US Naval History and Heritage Command, Washington D.C.

contributed to expanding knowledge and perceptions of the far south. In the early explorations around the margins and into the interior of Antarctica, artists served national and scientific agendas. They recorded species discovered, lands charted, and flags planted. The idea of the sublime was also a strong theme in their more lyrical work; expedition ships were depicted as vulnerable yet valiant, dwarfed by spectacular towering ice or battling ice-packed seas.

One of the best-known expedition artists is Edward A. Wilson, a physician and naturalist with Captain Robert F. Scott's *Discovery* and *Terra Nova* expeditions in the early 20th century. Straddling the scientific and artistic worlds of Antarctic exploration, and lauded for colour and technical accuracy, Wilson's work includes observational drawings of animals, landscapes, and atmospheric phenomena (Wilson & Wilson, 2011).

Cultural and technological changes in the mid-20th century saw the role of artists evolve when photography, pioneered in Antarctica by figures including Louis Bernacchi, Herbert Ponting, and Frank Hurley, eventually became the primary mode of documentary and scientific image-making. Nevertheless, the idea of the expedition artist endured, within American and later New Zealand military operations between the 1930s to the 1970s: David Abbey Paige accompanied Admiral

Richard E. Byrd in 1933–1935; Standish Backus and Robert Charles Haun documented Operation Deep Freeze I in 1955–1956 (see Figure 11.1); Peter McIntyre travelled south in 1957 and 1959; and in 1958 and 1964, respectively, Emil Schulthess and Sidney Nolan pushed the boundaries of contemporary artistic visions of Antarctica (James, 2006). During the 1980s and 1990s, access to the continent for artists of all disciplines expanded substantially through the development of national Antarctic program arts fellowships and through tourism, as noted above. At the turn of the 21st century, cultural diversity within the Antarctic artist alumni grew markedly when South American and Asian Antarctic programs began hosting artists, allowing a wider range of artistic voices to be heard.

Although the collective body of Antarctic visual arts material is expansive both in volume and conceptual exploration, recurring themes, highlighted below, speak to the value of the visual arts to critical engagements with Antarctica's natural and cultural environments, with creative inquiries into science, the environment, and human presence all playing important roles today.

Art and Science

A constant throughout Antarctica's human history is the enduring relationship between the visual arts and scientific inquiry. When Antarctica's devotion to science was formalised in the Antarctic Treaty, it became advantageous for artists to align with this dominant discourse, as it offered a route to experience the continent first-hand. Artists travelling with a national Antarctic program are encouraged to engage with contemporary science. Artists have collaborated with many disciplines of Antarctic science: diving under the ice to bring the marine world to the surface (Lily Simonson [2018]; Nobert Wu [2019]); scaling the southernmost active volcano to picture the alien landscape (Anne Noble [2014]; Michael Carroll [2019]); amplifying the microscopic world (Virginia King [2004]; Claire Beynon [2010]); drilling deep into the ice to chart climate histories and futures (Anna McKee [2017], see Figure 11.2; Gabby O'Connor [2017]); transforming atmospheric chemistry and physics into streams of color and sound (Andrea Juan [2007]; Donald Fortescue [2019]); throwing light onto the frozen lithosphere of the dry valleys (Diane Tuft [2014]; Craig Potton [2003]); and recording the pulse of the ice to reveal the heartbeat of Antarctica (Chris Drury [2008]; Anne Brodie [2008]).

Some of the most ground-breaking developments in contemporary research practice are found in transdisciplinary enquiry, where generative relationships between art and science create new knowledge. Claire Beynon was an artist and field assistant with biologist Dr Samuel S. Bowser, a specialist in the study of foraminifera (single-cell marine organisms). Their partnership yielded art-based developments in scientific experimentation: Bowser used micro-lithographic technology to transform a selection of Beynon's Antarctic drawings into substrate material for incubating foraminifera (Beynon, 2010, p.87). Gabby O'Connor was embedded within an ocean physics research team. Her scaled photographic portraits of super-cooled

FIGURE 11.2 Anna McKee. WAIS reliquary 68,000 years [detail]. Studio installation. Image credit: Joe Rudko.

ice platelet crystals generated data for scientific modeling of sea ice formation (Stevens, O'Connor and Robinson, 2019). In both instances, these collaborations resulted in numerous artworks and exhibitions of the collaborative investigations. O'Connor's exhibitions *Data Days* and *Studio Antarctica* presented micro and macro explorations of Antarctic ice – from single ice crystals through to the role of sea ice in a global ocean and climate context. Visual art has long been utilised to make scientific knowledge accessible. The distillation and communication of complex ideas through the visual medium can engage viewers on both cognitive and emotional levels to support understanding and appreciation of the Antarctic environment and the changes taking place within its ecologies.

Human Presence

Artistic explorations of Antarctica are by no means limited to the scientific realm. Artists have a vital role in exploring human cultural and political engagements with the Antarctic space. Challenging stereotypes and belying the myth of a pristine continent, artists have shown that human presence in Antarctica can be messy and confronting. Images of wildlife camouflaged among abandoned buildings and piles of debris (Simon Faithfull [2005]), industrial-looking field stations and infrastructure sullying the white landscape (Jan Senbergs, see Boyer [1988]), and photographic evidence of human waste (Anne Noble [2014]) reveal an ugly truth of human environmental degradation. Antarctic ideological environments are equally problematic. *Bitch in Slippers: Antarctic Inventory* (2008) is Anne Noble's photographic record of vehicles within the US McMurdo station fleet. Each vehicle is personalised with a name, mostly women's names, but others include "Shagnasty's Nightmare," "Hot Lips," "Hysteria," and "Mental Case" (Noble, 2014). The work exposes the gendered nature of the station's culture. By documenting the machines and their names, the artist directs the viewer's gaze toward a manifestation of derogatory attitudes that have been allowed to flourish in a male-dominated environment.

A series of three works from Lucy and Jorge Orta's Antarctic collection draws together environmental and political themes. In the installation *Antarctic Village: No borders* (2007) – a symbolic settlement of tents draped in national flags – the continent is reimagined as a sanctuary for climate change refugees. The artists flew their *Antarctica Flag* (2007–2021) on the continent and in Paris during the ArtCOP21 Climate Festival ahead of UN climate talks. The flag design, which blends the national emblems of Antarctic Treaty nations, symbolises a blurring of boundaries to overcome national division to create a unified whole. Finally, the artists' *Antarctic World Passport* (2022) requires holders to agree to a global citizen charter, which includes an addition to the Declaration of Human Rights allowing the free movement of people across borders. Notably, the artists were hosted by Dirección Nacional del Antártico, the Argentinian Antarctic program, meaning the village and flag were installed in one of the most contested spaces on the continent – an area of the Antarctic Peninsula where Argentina, Chile, and the United Kingdom each maintain a territorial claim. The work compels the viewer to consider the centrality of Antarctica within the world's interconnected social, political, and environmental realms in the context of an escalating climate change refugee crisis. The artists advance the notion of Antarctica as a site of global commons and supranational geographies; Antarctica is a place belonging to no-one yet a place to which everyone belongs. The siting of the work served to reinforce the artists' argument and aspirations for geopolitical reconfiguration.

Music

Antarctica and the Southern Ocean have inspired the composition of myriad musical works since the earliest days of regular human engagement with the region during the Heroic Era. While some of these works have emerged from in-person encounters with the icescape and surrounding ocean, others have relied more heavily on the imagination, informed by pre-existing images, sounds, and stories. The rich body of musical responses to the region features a diversity of musical genres and styles, from high-profile Western art (or "classical") music to soundscape-based composition to modern-day hip hop. Although there are some examples of non-Western music created in connection with Antarctica (such as shakuhachi music from the Japanese Antarctic Expedition of 1910–1912, songs created during the Second

Soviet Antarctic Expedition in the mid-1950s, and various popular music videos from around the world on YouTube), the vast majority and most widely known musical works created in association with Antarctica to date emerge from Western cultures. Within this latter corpus, three recurring extra-musical themes emerge that provide useful frames for considering these works: the heroic, the sublime, and the fragility of the environment.

The Heroic

The earliest musical works created in connection with the far south were composed during Heroic-Era expeditions when activities such as songwriting provided a welcome distraction from boredom, an alternative means of recording experiences, and valuable entertainment for all. Numerous diaries and published materials related to the expeditions include original song lyrics (typically set to existing popular tunes), many of which project heroic sentiments. For example, two sets of lyrics composed during the Australasian Antarctic Expedition (1911–1914) – "Aurora Australis" (sung to "The Lord High Executioner" from Gilbert and Sullivan's *The Mikado*) and the "Southern Sledging Song" (sung to the tune of popular sea song "Sailing, sailing") – refer to the expeditioners as "conquerors of Adelie Land" and "men of the Southern Trail … [who] rise from each defeat," respectively (Laseron, 1913). Additionally, at least one collection of songs with original music as well as lyrics survives from the period: Gerald Doorly's *Songs of the Morning*, composed during the resupply of Scott's *Discovery* expedition in 1902. Doorly's songs highlight key moments in the journey south, including braving seas that are "mountains high" in the "blinding sleet and snow" (in the songs "Yuss" and "Southward"). The songs are now available to audiences worldwide through a published score and recording (Doorly, 1943).

The first musical responses to Antarctica by professional composers also explore heroic themes, especially in relation to Scott's last (*Terra Nova*) expedition. The German opera *Das Opfer* ('The Sacrifice'), composed in 1937 by 12-tone composer Winfried Zillig to a libretto by Reinhard Goering, is perhaps the first large-scale musical work associated with Antarctica. It tells the story of Scott's fateful polar journey, focusing particularly on the final moments of Lawrence Oates (Leane, Philpott and Nielsen, 2014). This was followed by English composer Ralph Vaughan Williams's landmark music inspired by the same story: the score for the 1948 film *Scott of the Antarctic* and his subsequent *Sinfonia Antartica*, which has remained popular in concert halls since its premiere in 1953. More recent works that deal with Heroic-Era narratives include two chamber operas by Australian composers – *Fire on the Snow* (2012) by Scott McIntyre and *The Call of Aurora* (2013) by Joe Bugden, about Scott's final expedition and the Australasian Antarctic Expedition, respectively – and the opera *South Pole* (2016) by Czech composer Miroslav Srnka, which focuses on Scott and Amundsen's race to the Pole. In contrast, Mary Finsterer's, 2022 opera *Antarctica* is much more abstract in its approach, focusing on archetypal seekers of the unknown rather than specific heroes.

The Sublime

The sublime nature of the Antarctic environment – that is, its capacity to evoke feelings of awe and fear – is recalled in many musical works, including in the most prominent compositions related to the region. Most famously, Vaughan Williams's main theme for both his film music for *Scott of the Antarctic* and his *Sinfonia Antartica* features an ascending profile, spaciousness in its orchestration and a foreboding character that combine to convey both the vast scale and threatening nature of the icescape. In his quest to represent the "terror & fascination" of the region, Vaughan Williams incorporated unconventional instruments into the orchestral texture, including a wind machine and wordless female voices (Philpott, Leane, and Quin, 2020, p.116). Although Vaughan Williams never visited the far south (instead taking inspiration from literature), his fellow British composer Peter Maxwell Davies did travel south before composing his own *Antarctic Symphony* (2000), intended as a sequel to *Sinfonia Antarctica*. Like Vaughan Williams, Davies utilised various unusual instruments to represent the unique environment, such as a biscuit tin filled with broken glass and three different lengths of builder's scaffolding used as percussion instruments to suggest the sound of an icebreaker smashing through sea ice.

In contrast to the ominous mood of these examples, Australian composer Nigel Westlake's immensely popular *Antarctica* suite for guitar and orchestra (1992) takes a lighter approach to representing the region in sound. Based on the film music Westlake composed for the IMAX documentary *Antarctica: An Adventure of a Different Nature* (1991), the suite begins with sparse, static harmonies and dramatic gestures to represent the arid and immense nature of the plateau in the opening movement ("The Last Place on Earth") but also includes highly lyrical and playful moments, such as in the third movement ('Penguin Ballet'), which vividly portrays the lively, fluid movements of penguins swimming underwater.

Fragility

The vulnerable nature of the far southern region, especially its susceptibility to human-induced environmental change, is a strong theme that has emerged in music in recent years, particularly in the works of composers and sound artists who have visited in person. Many such artists have made field recordings for use within their works. San Francisco-based composer and performer Cheryl Leonard, for example, utilises field recordings from Antarctica and the Southern Ocean in her collection of ten pieces, *Antarctica: Music from the Ice* (2009–2015). In "Rookerie" and "Fluxes," for instance, she innovatively combines excerpts from her recordings of Adelie penguins and the Southern Ocean, respectively, with sounds from instruments crafted from penguin bones, rocks, and shells (collected with a permit; see Figure 11.3) to convey to audiences the sounds of the changing environment of the Antarctic Peninsula, and also, as Leonard puts it, to "evoke distress about the

FIGURE 11.3 A selection of musical instruments crafted from natural objects collected in Antarctica by Cheryl Leonard. Image Credit: Cheryl Leonard.

threats that [these] changes … pose to these vibrant, unique marine ecosystems" (qtd in Meyers and Philpott, 2021, p. 71).

Although working in a completely different genre, the American composer and experimental hip-hop musician Paul D. Miller ("DJ Spooky") also employs field recordings that he made in Antarctica in combination with sounds from other instruments, as well as electronic music based on scientific data, in works such as *Terra Nova: Sinfonia Antarctica* (2008), which aim to engage audiences with the far south and important environmental issues affecting the region (Philpott, 2020, p. 89). Similarly, the 2016 stage show *Antarctica: A New Musical* foregrounds environmental concerns, with lyrics such as "We can rise above / Blue planet needs our love" (McLaren, arr. Wood, 2016), highlighting the fragility of the far south to human impacts.

Collectively, the rich body of Antarctic and Southern Ocean-related music reaches large and diverse audiences, from those attending concert halls or exhibits/installations at museums and art galleries to those accessing sound recordings on CD, radio, via films, and through online formats that are available for listening in the home or anywhere. Through these diverse media, the wider public can connect with the far southern region more readily than ever before and engage with some of the key themes and issues related to it today, all via the highly accessible and affective medium of music.

Literature

With so much influential nonfiction written about the Antarctic region – early explorers' narratives, contemporary travel accounts, environmental writing, and popular science – the existence of a large body of imaginative literature that engages with the continent is easily overlooked. While not as visible as nonfiction accounts, these imaginative written responses are vital to understanding the cultural assumptions and expectations that invisibly undergird humanity's relationship with the far south. While a summary of several hundred years of literary response is beyond the scope of this chapter, two contemporary examples provide a useful way into the different strands of this imaginative tradition.

The first example is bestselling British writer Tom Rob Smith's dystopian science fiction novel *Cold People* (2023). While mostly set in the near future, the narrative commences "two thousand years ago" (p.1) with the voyage of Ui-te-Rangiora who, encountering the southern ice, concludes "only a savage people could survive in such cold" (p.7). The novel explores this theme through an unexpected device: the arrival of alien beings who for reasons unknown command all of humanity to move to the Antarctic continent within 30 days and vaporise anyone who fails to comply. Twenty years after this enforced exile, the remaining humans eke out an existence among the ice. All of the old hierarchies that structured human society have been overturned in humanity's new home at the bottom of the Earth: military warships become "floating communities" (p.359), people happily converse in both English and Mandarin, and ex-presidents run the local bar while an economics professor becomes the new leader – something that "never would have happened if the world hadn't been turned upside down" (p.406). However, scientists disrupt this relative harmony by conducting radical genetic experiments that produce cold-adapted progeny, believing that this is the only way to stop the species' inevitable extinction. Centring on the experience of a genetically altered female protagonist, the novel explores the question of how far such technological adaptation can go before humans become alien to themselves.

To anyone familiar with the Antarctic literary tradition, *Cold People* has strong echoes of previous narratives: Paul McAuley's *Austral* (2017), for instance, focuses on a genetically altered woman living in the Antarctic Peninsula in a warmer future; in John Batchelor's sprawling work *The Birth of the People's Republic of Antarctica* (1983), islands just off the Peninsula are the site of refugee camps for people exiled from a war-torn world; in Sophie Wenzel Ellis's short story "Creatures of the Light" (1930) – one of the earliest pieces of Antarctic fiction written by a woman – a scientist working at a secret Antarctic laboratory takes genetic experiments too far when he creates a highly evolved but entirely merciless superhuman.

Smith's novel is then the latest in a long line of fictional narratives in which Antarctica is both a refuge from world-wide catastrophe and a place to experiment with social and political norms – to start humanity anew. The utopian idea of an improved, nationless, more egalitarian society in Antarctica – an idea closely linked to the continent's multilateral governance under the 1959 Antarctic Treaty – can also be found in several previous novels, including Sakyo Komatsu's *Fukkatsu no hi* (1964; published in English as *Virus,* 2012), David Poyer's *White Continent* (1980), and Kim Stanley Robinson's *Antarctica* (1997). Countering the egalitarian possibilities that Antarctica's seemingly blank and upside-down space enables is a darker, social Darwinist vision in which only the fittest – often interpreted in racialised terms as the whitest – can or should survive in the far south. With its roots in early works, such as *Symzonia* (1820), by the pseudonymous "Adam Seaborn," and Edgar Allan Poe's *Voyage of Arthur Gordon Pym of Nantucket* (1838), this tradition was at its height in interwar novels, such as Edison Marshall's *Dian of the Lost Land* (1935) and Beall Cunningham's *The Wide White Page* (1936), and is satirised in later responses, such as Rudi Rucker's *The Hollow Earth* (1990) and Mat Johnson's *Pym* (2011).

Contrasting strongly with *Cold People* is an Antarctic-set novel published only a few months previously, *Terra Nova* (2022), by US novelist Henriette Lazaridis. Taking its title from that of Robert F. Scott's second, fatal polar expedition of 1910–1913, *Terra Nova* rewrites the famous historical story of the "race to the pole." In Lazaridis's narrative, Viola Heywood, photographer and wife of a fictional British expedition leader, is also the lover of another member of the polar party, the expedition photographer. In this version of Antarctic exploration history, a competing Norwegian team perished on return from the Pole. The survivors – the British team – craft a narrative of precedence that suits their own purposes, although Viola's subsequent discovery of their lie changes all of their lives forever. Meanwhile, she has been using her photographic skills to document and empower suffragette hunger strikers, so that both her artistic achievement and her subjects' sacrifices are constantly paralleled to rigours of Antarctic exploration. Viola considers her photographic exhibition to be "Her place, her creation, her Pole" (p.160).

Variations on Lazaridis's themes – the mutability of exploration stories, the gendered nature of early Antarctic encounter, the metaphorical potential of polar journeys to express other forms of suffering and resilience – feature in many earlier literary works. Examples include historical novels such as Kåre Holt's *Kappløpet* (1974; published in English as *The Race* [1976]), Beryl Bainbridge's *The Birthday Boys* (1991), and Rebecca Hunt's *Everland* (2014); short stories such as Ursula Le Guin's "Sur" (1982); and plays such as Douglas Stewart's *Fire on the Snow* (1944), Ted Tally's *Terra Nova* (1981), Manfred Karge's *Die Eroberung des Südpols* (1986; published in English as *The Conquest of the South Pole* [1989]), Mojisola Adebayo's *Moj of the Antarctic* (2008), and Patricia Cornelius's *Do Not Go Gentle* (2011). While these works might seem backward-looking in their interest in retelling the classic stories of the continent's exploration, they are equally interested in questioning received understandings of this history and rewriting assumptions about what kind of people – in terms of race, class, gender and sexuality – "belong" in Antarctica.

The two examples discussed here – *Cold People* as the exemplar of the science fictional and dystopian strand of the Antarctic imagination, and *Terra Nova* as the latest incarnation of a more historical and literary tradition – in no way exhaust the corpus of Antarctic literature. There has been little space here, for example, to discuss the rich body of poetic works dealing with the far south, which range from long narrative poems to short lyric responses and include works by critically acclaimed poets such as Pablo Neruda, Les Murray, Dorothy Porter, Bill Manhire, and Nikki Giovanni. This summary has likewise sidestepped the "Antarctic gothic" tradition that runs from Samuel Taylor Coleridge's poem "Rime of the Ancient Mariner" (1798), through H.P. Lovecraft's novella *At the Mountains of Madness* (1936), to a whole series of more recent science-fiction-horror-thrillers, such as Greig Beck's *Beneath the Dark Ice* (2009). Nonetheless, these two contemporary examples serve well to show how closely the contemporary Antarctic imaginary is entangled both with the continent's real history and with earlier literary works. While the stories contained in these texts may not be factual in the sense of nonfiction narratives, their effects are no less real, for they both reflect and produce ways of thinking that impact humanity's engagement with the Antarctic continent.

Visual arts, literature and music all make important and interrelated contributions to our critical enquiries and understandings of the nature and cultures of the far south. However, it is not just works about Antarctica that help to shape cultural connections with the far south. The ways Antarctica is studied, interpreted, and curated in situ are particularly important in the 21st century context as the continent becomes more and more accessible via tourism channels and as the spotlight is shone on the environmental footprint of human activities past and present. It is therefore useful to consider how both heritage and tourism function in Antarctica and interact to shape perceptions of wilderness, aesthetic, and environmental values.

Objects in Antarctica: Understanding Heritage through Things

Objects (from knives to socks to huts to vessels) have necessarily mediated human presence and experience in Antarctica (Senatore, 2020, De Pomereu and McCahey, 2022). Since the first human sighting of Antarctica, its exploration, exploitation, visitation, and occupation have been enabled by the presence and use of objects. Within the framework of capitalism, industrialisation and colonialism expansion processes, the continent saw a rapid increase in the rate at which objects spread across it. During the first decades of the 20th century, different nations extended and maintained more stable settlements. The desire to possess, colonise, and appropriate space, or to show a permanent and continuous presence in Antarctica, was fulfilled by things. By the end of the 1940s, much of the continent was subject to national claims until the signing of the Antarctic Treaty in 1959, which put these claims on hold.

In the frame of the Antarctic Treaty, things began to play a political role, as certain buildings and artefacts were identified as having significant heritage value and some parties committed to preserving and managing them. At that time, "tombs, buildings and objects of historic interest" (Recommendation I-IX

(ATCM I - Canberra, 1961) began to contribute to the construction of national identities and nationalistic narratives. Any party involved in the Antarctic Treaty could nominate a historic site to be included in the List of Historic Sites and Monuments (HSM), which came into being in 1972. This document contributed to building a shared understanding of heritage in the frame of the Antarctic Treaty System (ATS). Most of the protected HSMs have represented a memorable past in which national narratives and interests have been connected (Barr, 2022). Historic narratives about scientific exploration have largely dominated the field of heritage as well as the commemorative elements (i.e., memorial plaque, cairn, bust, statue, flag mast) that were deliberately brought into or built in Antarctica to commemorate a particular historical event, which were then nominated by National Parties for the HSM list. In this sense, the HSMs have contributed to the universalisation and homogenisation of ways of perceiving and narrating Antarctica's past.

During the 20th century, while technological developments and innovations increased and the possibilities for transporting goods broadened, living and working in Antarctica also meant accumulating things. Human-thing relations gradually diversified, increasing in complexity and scale, but at the same time, some things gradually acquired a bad reputation and started to be considered "polluting." The prevailing interest in environmental protection encouraged researchers, policymakers, and other actors working with the ATS to find ways to avoid or minimise human impact, and consequently, material remains were involved in environmental discussions.

The introduction of the Madrid Protocol initiated the widespread clean-up of abandoned objects and buildings across Antarctica and brought changes to the way people and things interacted there. Conservation is about loss; deciding what to protect is at the same time deciding what is going to be lost (De Silvey, 2017). Because of the ill-defined concept of waste and the way in which things were categorised by bearing or not bearing historic value, environmental protection measures in Antarctica have reinforced dominant historic narratives (Senatore, 2020), neglecting some human stories and actively erasing nonhuman stories –- for example, the removal of ice or microorganisms in timbers, among others (Flyen & Thuestad, 2022). This has implications for how Antarctica is valued into the future.

The general nostalgic approach devoted to restoring buildings and conserving the objects found inside them was carried out over decades. Conservation projects focused on HSMs led to an attempt to save these valuable objects from decay, and their conservation was assumed to be the responsibility of national parties. In the late 1960s, the huts associated with the Heroic Era located in the Ross Sea, the Commonwealth Bay and the Antarctic Peninsula regions began to be conserved and restored. Abundance, diversity, specificity, and even sophistication characterised things inside the huts. It is interesting to note that many things were abandoned there, despite still being useful (e.g., uneaten food and unused objects), including explorers' personal items, such as clothes, books, diaries, and photographs. Today these historic sites are cared for by trusts – the New Zealand Antarctic Heritage

FIGURE 11.4 Base A, Bransfield House and the boatshed, Goudier Island. HSM61, Port Lockroy. 2015. Image credit: Adele Jackson.

Trust operates in the Ross Sea region, where the huts of expeditions led by Carsten Borchgrevinck, Ernest Shackleton, and Robert Falcon Scott are located, along with Edmund Hillary's Trans-Antarctic hut, while the Mawson's Huts Foundation is active both in Commonwealth Bay, site of the base used by Douglas Mawson in 1911–1914, and in Hobart, where a replica of the original hut was built near the waterfront. In these locations, the stories of well-known Heroic Era explorers dominate the discourse around the huts. The UK Antarctic Heritage Trust is active in the Antarctic Peninsula and is well-known for the historic site "Port Lockroy," on Goudier Island (Figure 11.4). This HSM has become one of the most popular destinations on the Antarctic Peninsula, featuring a museum that highlights past British science and exploration in Antarctica as well as a post office and gift shop – where many of the books for sale recount the stories of the Heroic Era. These sites can therefore perpetuate particular visions of Antarctica and continue to privilege particular cultural positions in relation to the continent.

A focus on material culture in the Antarctic shows how the representation of the Antarctic continent as the last wilderness has overlooked the diversity of human connections to Antarctica since the 19th century. The list of HSMs could be understood as the material expression of the dominant historical narratives. Their designation is often not inclusive, excluding stories that convey capitalism; colonialism; memories of unrestricted fishing, whaling and sealing; and territorial claim conflicts that contradict the vision of Antarctica enshrined in the Protocol on Environmental Protection as a natural reserve devoted to science and peace. Although in recent decades, studies in the humanities and social sciences have connected Antarctica with cultural processes on a global scale, countering the dominant historical narratives, environmental protection measures have contributed to a prevailing image of an isolated wilderness untouched by humans. Moreover, heritage discourses have left no place for local narratives that reflect stories that connect people to places and objects in different temporalities of Antarctica, including the present.

Selling Antarctica

The historic huts are one of many aspects of the Antarctic that draw people who are willing to pay to see the place. With the continent largely inaccessible to independent travellers, most visitors join cruises, which mainly operate in the Antarctic Peninsula region. These voyages are often marketed as "expeditions" rather than "cruises." The word "expedition" carries intrepid connotations of exploration, which is a good conceptual fit for a remote continent of snow and ice – it also explains the flexibility of any given itinerary, which is impacted by weather and ice conditions and the activities of other vessels nearby. While each voyage sets sail with a planned itinerary, this is not finalised – nor made public to the travellers – until the night before a landing. A vessel scheduler coordinated by the body that manages the industry (The International Association of Antarctica Tour Operators) ensures that Site Guidelines are respected and the human footprint on a particular site does not exceed the limits that have been set (e.g., of visitors ashore and number of vessels in a 24-hour period).

Nevertheless, the Antarctic tourist experience is carefully choreographed (Roura, 2010, p.198). Expedition Leaders and Captains confer to ensure that guests encounter a range of wildlife (whales, seals, different penguin species) and are offered highlights, such as a continental landing. The marketing imagery that guests view prior to their own Antarctic trip helps to shape expectations around what they can expect to encounter – the expedition team on board the vessel is then charged with delivering this polar product (Nielsen, 2023). This delivery includes wrap-around educational materials – what the guides talk about and where they direct the tourists' gaze have a big impact on the overall experience of Antarctica. Curation of place therefore plays an important role in an Antarctic tourist expedition.

The cultural background that tourists bring to Antarctica is important because the stories of the far south that circulate in any given community – be they about Heroic Era figures, inhospitable weather, or climate change – shape perceptions of the place and colour guest expectations. Wilson Cheung and colleagues detail how the Chinese tourists involved in their study demonstrated a "different understanding of environmental protection" to their Western counterparts (2019, p. 197), while Rupert Summerson has detailed how connotations of the word "wilderness" range from the desolate to the environmentally valuable, depending on cultural and language expectations (2012). These expectations can also be a motivating factor for tourists. For instance, those with a particular interest in Western polar history might be drawn to an itinerary that travels "in Shackleton's footsteps" (Aurora, 2023) or "retrac[es] Heroic Age expeditions" (Ponant, 2023). Daniela Cajiao et al. (2022) identify four key motivations for Antarctic tourists: "experience & learning, adventure into Antarctica, social bonding, and trip of a lifetime." Such motivations can change depending on the level of knowledge about the continent and the sorts of portrayals of the place with which people are familiar – including those that appear in ephemeral forms of popular culture.

One way to identify the ideas about Antarctica that circulate in popular culture is to examine advertisements. As Judith Williamson explains, rather than create new meanings, advertisements "are the great recyclers of images: they feed off the iconography of the present, at the same time as perpetuating it" (2010). While some advertisements feature images of a product in situ on the ice (a promotional technique common throughout the Heroic Era), a company does not need to have an existing Antarctic link to call upon polar tropes in an advertising campaign. Rather, Antarctic imagery can be used to create an association between a product and any of the dominant stories that circulate about the place. Heroism and extremity cast Antarctica as a place for humans or machines to battle the environment and triumph in the face of adversity. In advertisements for products, such as watches (Nirvana, Rolex), vehicles (Volkswagen, Hyundai), and high-tech clothing (North Face, Shackleton), Antarctica becomes "the ultimate testing ground for technologies" (Nielsen, 2019, p. 119). In contrast, framings of Antarctica as a pure place present visions of a continent devoid of human presence and impacts – paradoxically, this has been a particularly valuable framing for those offering products from Antarctica, such as producers of krill oil (Blackmores) or nutraceuticals (such as those containing the glycoprotein "Antarcticine"). More recently, the continent has become shorthand for climate change on a global scale, with icy imagery (and more specifically, melting ice) being used as a visual reference point for the otherwise invisible phenomena of anthropogenic warming. Such imagery has been employed both by environmental organisations (WWF, Antarctic and Southern Ocean Coalition) and by companies wishing to showcase their environmentally friendly credentials (including ABB's, 2002 advertisement and Westpac Bank's 2008 campaign that both featured penguins and highlighted claims to environmental stewardship) (Nielsen, 2019, p.122). When considering cultural connections with Antarctica, everyday depictions of the place can be revealing of the ideas associated with the place at any given time and place. With both Antarctic tourism and advertising, cultural connections and commercial connections go hand in hand.

Antarctic Gateway Cities

Tourists, like other visitors to the continent, travel through a small group of far southern ports known as "Antarctic gateway cities." These comprise the five prominent gateways of Ushuaia, Argentina (the jumping-off point for most tourist cruises); Punta Arenas, Chile; Christchurch, New Zealand; Hobart, Australia; and

Cape Town, South Africa (see Figure 0.1). Several other small ports, including Stanley in the Falkland/Malvinas Islands and Puerto Williams in Chile, also have good claims to gateway status. The five main gateway cities have strong cultural connections with the far south, which are showcased through public art and heritage (see Figure 11.5), walking tours, interpretative centres, visitor attractions, and specific festivals. These cities, then, create their own version of vicarious Antarctic tourism. However, their Antarctic identity is more than simply branding. Antarctica is felt as a presence in these places, rather than as a remote and far-off place. There are many opportunities for the Antarctic gateway cities to strengthen their public-facing connections with the far south and to learn from each other about successful public engagement strategies (Southern Ocean Action Plan, 2022). Juan Francisco Salazar and Elias Barticevic argue that these cities must strive to construct "forms of Antarctic identity" that reflect "the cultural values of Antarctica" (2015, p.589). The recent *Antarctic Cities* report sets out a blueprint for "reimagining" these cities as future stewards of the continent (Salazar et al., 2021, p.1).

FIGURE 11.5 A tribute to Antarctic explorer Louis Bernacchi sculpted by Stephen Walker in the Antarctic Gateway city of Hobart, Tasmania. Image credit: Bjørn Christian Tørrissen. Licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license: https://creativecommons.org/licenses/by-sa/3.0/deed.en

Looking Forward

Examining various forms of cultural production – visual art, music, literature, and advertising – helps to reveal the dominant values associated with Antarctica. It also reveals the cultural conditions that contributed to and maintain the view of Antarctica as a place to be protected that predominates today. Climate change – the impact of which is amply described elsewhere in this volume (see Chapters 4–7 and 9) – is also playing an increasingly large role in Antarctic literature and art. The former includes not only science fiction novels such as McCauley's *Austral* and Robinson's *Antarctica* (mentioned above) but also ecothrillers (e.g., L.A. Larkin's *Thirst* [2012]), historical fiction (Dennis Glover's *Thaw* [2023] and more experimental literary works (e.g., Ilija Trojanow's *Eis Tau* [2011], published in English as *The Lamentations of Zeno* [2016]). In visual art, a growing sense of anxiety concerning anthropogenic environmental impacts has been evident at least since the beginning of the 21st century. Melting polar ice has become a symbol for a planet facing climate crisis (Eliasson, 2014). Artists have lamented ice loss through various media: some have used the materiality of melting ice to create images and installations (Xavier Cortada [2007]; Veronika Podlasova [2017]; Wayne Binitie [2021]); others have photographed ice or used photographic records of ice as their source material (Camille Seaman [2008, 2014]; Jean de Pomereu [2021]; Zaria Forman [2019]). A work that comprehensively distils the relationship between ice and a changing climate is Anna McKee's *WAIS Reliquary: 68,000 Years* (see Figure 11.2). Described as "a silent and abstracted representation of 68,000 years of temperature" (McKee, 2017), the work highlights the recent rapid and accelerating warming of the climate. The challenge of future cultural responses to Antarctica – whether through literature, art, music, heritage, gateway cities or tourist interpretation – is to engage with the threat of climate change in a way that spurs people to action rather than despair.

The "last great wilderness" of Antarctica and the Southern Ocean is not a stable nor timeless signifier: the region has meant different things to people at different points in time. People have been attracted to the place for a range of reasons, including commercial, geopolitical, and scientific interests. Values are culturally dependent, reflecting what is valued in particular societies: "the values that people bring to the Antarctic are rooted in their experience elsewhere, at home, outside the Antarctic" (Neufeld, 2014, p249). Because of its relatively young human history, the Antarctic Region can appear as a blank canvas upon which humans can project their hopes and desires. Antarctica has been figured as a place for heroes, where men battle the elements to triumph over nature – as seen in endless retellings of early exploration narratives, such as the "Race to the Pole." It can also be framed as a place that is fragile, and vulnerable to anthropogenic climate change – as seen, for example, in ecothrillers and other recent popular texts. As Salazar argues, in the age of the Anthropocene "we cannot continue to think of Antarctica as the end of the Earth" (2013, p.67). Instead, it is a place connected to the rest of the world – in terms of climates, currents, pollution, and human narratives. It is useful then to think not of one Antarctica, but of many – the region is deeply storied, and these stories accumulate and shift year upon year, much like the ice of the Antarctic continent itself.

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12

CONCLUSIONS

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Antarctica and the Earth System

The chapters of this book have emphasised the centrality of Antarctica and the Southern Ocean in multiple aspects of the Earth System. The importance of these connections can be partially envisaged by considering the financial value of ecosystem services provided by Antarctica to the rest of the world (conservatively estimated at US$180 billion), or by the financial cost of sea level rise in 2100 caused by Antarctic Ice Sheet melt (estimated at >US$60 billion per year even with low greenhouse gas emissions and optimal adaptation – rising to around US$1 trillion per year with no adaptation). Of course, such financial estimates, whilst vast, only represent part of the true scientific, societal and cultural value of Antarctica to humanity, even aside from the intrinsic value of the region.

Numerous key messages have emerged from this book, many of which point to priorities for future actions, scientific research and policymaking (Figure 12.1). Underpinning several of these is a critical need to better understand the drivers of observed and ongoing changes in Antarctic climate. Many of these changes have been attributed to global atmospheric forcing, including human-driven perturbations such as greenhouse gas-driven warming and ozone depletion. Superposed on these are natural phenomena such as coupled modes of climate variability, some of which can transmit tropical and equatorial signals to high latitudes, though it should be noted that the strength and frequency of such events are themselves susceptible to global climatic forcing. Resolving this scientific complexity demands comprehensive networks of sustained *in situ* observations, linked to satellite observations and coupled models for their current and future trajectories to be adequately addressed. However, there are persistent gaps across this capability due to the remote and harsh nature of the Antarctic environment.

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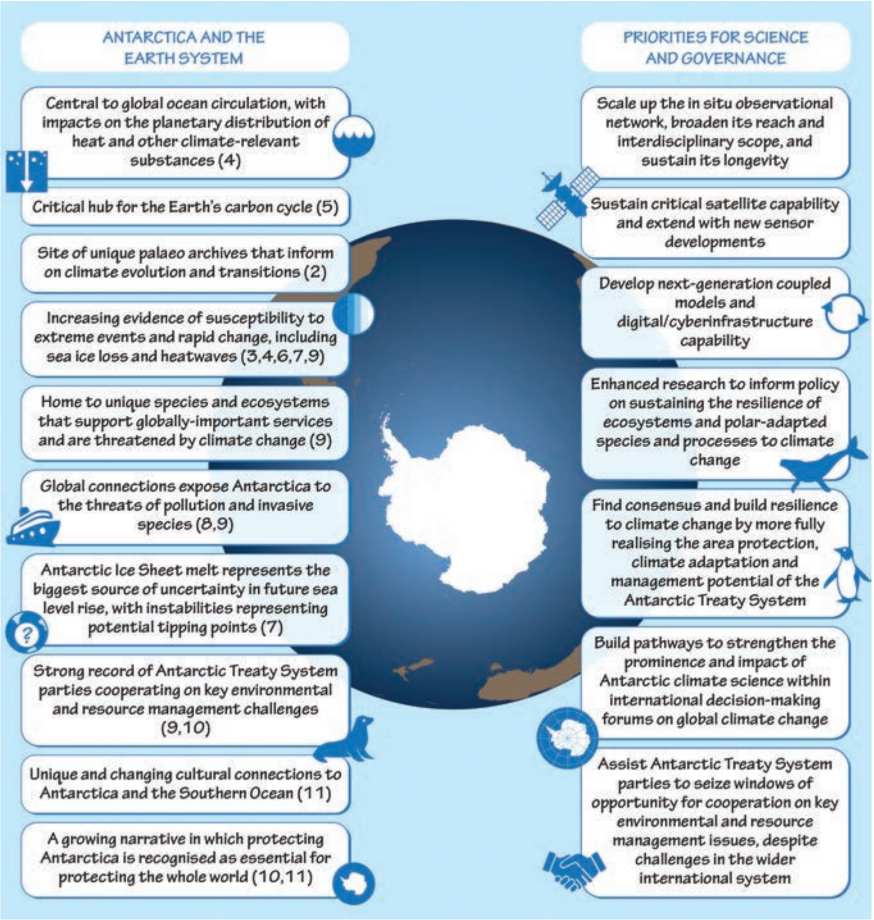

FIGURE 12.1 Key connections between Antarctica and the rest of the Earth System, and priorities for science and governance Relevant chapters are cited in brackets.

Sea ice serves as a clear exemplar of the potential for rapid change around Antarctica. This sea ice cover has long been known as dynamic and variable on timescales from days to decades, incorporating one of the largest annual cycles on Earth. However, satellite monitoring has revealed a very rapid dwindling of Antarctic sea ice cover since 2016, following a gradual expansion in the preceding decades. The full causes of this are, at the time of writing, the subject of active research, but include both atmospheric and oceanic drivers and complex feedbacks. There is increasing thought that this change may represent the transition to a new state, with global climatic implications via albedo changes and dense water production, and ecosystem consequences through the loss of a key habitat for ice-dependent species.

There is mounting evidence that the changing atmospheric and cryospheric forcings of the Southern Ocean (including a contracting polar vortex, retreating sea ice and accelerating ice sheet melt) may be driving a major reorganisation of the Southern Ocean overturning circulation. Given the circulation's importance to planetary climate on timescales of decades and longer, via its moving of vast quantities of heat and other climatically-important tracers around the world, this has profound implications for the rest of the planet, its ecosystems and inhabitants. However, accurately assessing the structure, rate and global consequences of this reorganisation poses formidable observational and methodological challenges, due to the circulation's spatially-distributed nature, its vast scales, and the inaccessibility of many focal sites of overturning such as areas of dense water production at the Antarctic margins.

Alongside the Southern Ocean's important role in global ocean circulation, it is also a critical hub of Earth's carbon cycle, whose variability readily and profoundly impacts global atmospheric carbon dioxide and climate. The amplitude – and even the sign – of these impacts can however be extremely challenging to predict, due to the Southern Ocean's central involvement in a suite of physical and biogeochemical climate-system feedbacks. Achieving a step advance in predictive capability will require substantial leaps in process understanding in a range of science areas – from the turbulent dynamics controlling ocean ventilation and physical carbon uptake and storage to the micronutrient-physiology dynamics shaping biological uptake by phytoplankton or the biogeochemical regulation of clouds over the Southern Ocean.

One way to gain more insight into the operation of the Antarctic and Southern Ocean system is via the unique perspectives on climate variability and ecosystem changes that are available from palaeo-environmental archives, including ice cores, ocean sediment cores, lake sediments, and so on. Each of these contributes vital information on conditions that prevailed on Earth in the past, how they evolved into the conditions we are living in today, and, by extension, which future trajectories are possible under different scenarios. Critically, they provide insight into transitions between environmental states, including knowledge on the potential for rapid climate shifts and the passing of tipping points, and the timescales upon which such changes are irreversible. Extending current knowledge and using new techniques to better integrate this understanding into enhanced predictive capability is a high priority.

Perhaps the most tangible impact that Antarctica can have across the planet is via sea level rise. The ice sheet is presently undergoing a dramatic shift, with some major sectors shrinking at accelerating rates. It is widely agreed that Antarctic Ice Sheet mass loss will continue for centuries to come and that this loss will result in substantial global sea level rise. However, the rate and ultimate extent of ice sheet waning and associated rising seas are the subject of deep uncertainty, leaving humanity significantly unprepared for what lies ahead. To address the ice sheet and climate model shortcomings underpinning such deep uncertainty, it will be necessary to radically advance our understanding of a range of key atmosphere–ocean–ice interaction and ice sheet dynamical processes, such as marine ice sheet and ice cliff instabilities. The complexity of the scientific problem and the scale of what is at stake for global society makes the prediction of the Antarctic Ice Sheet's future one of the most critical and pressing challenges facing us today.

Concerning biodiversity, it is known that sealing, whaling, fishing and human presence have been the major historical threats in the Antarctic. However, the most significant drivers of future ecosystem change are likely to be climate change and ocean acidification, which are mostly caused by human activity outside the region. There is a pressing need for enhanced research to be coupled with a management focus on what is needed to sustain the resilience of Antarctic and Southern Ocean ecosystems in the face of global threats from future change to many polar-adapted species and processes. At present, our scientific knowledge of these ecosystems as a whole is insufficient to closely manage increased human presence and allow any significant expansion of fisheries. Current fisheries levels may in fact threaten the long-term resilience of marine ecosystems, particularly for high-latitude fisheries. Across both marine and terrestrial ecosystems, there is a need for evidence-informed projections of where to establish protected areas to enable resilience and to conserve biodiversity in the face of global threats from climate change and ocean acidification.

Antarctica and the Southern Ocean are vulnerable to both local and globally-dispersed pollutant threats. Of these, the local pollutant threat is established, regulated, and relatively well understood, but the impacts of pollutants that are dispersed via atmospheric and oceanic pathways (particularly nanoplastics) are currently poorly understood. Human activities have led to substantial increases in the long-range deposition of pollution into Antarctic and sub-Antarctic regions; future climatic changes (including strengthened ice melt and increased precipitation as rainfall) will lead to enhanced (re)deposition, and possibly increased concentrations of globally-derived pollutants across Antarctic terrestrial and marine environments. Accordingly, understanding how pollutants might decrease the resilience of biological organisms and ecosystems to other stressors is an important research priority.

Whilst Antarctica and the Southern Ocean are geographically remote from major centres of population and much of the economic activity on our planet, human interaction there is still influenced by both regional and global geopolitics. The Antarctic Treaty System (ATS) has been remarkably successful in setting aside arguments over sovereignty and allowing the region to be used by all states involved for peaceful activities such as science, tourism and controlled fishing. However, the success of the ATS has also perhaps set unrealistic expectations about its ability to manage all political and other challenges that impact the region. Just as during the 1950s, when the ATS was formed, tensions and changes in the wider international political system are affecting relations between states in Antarctic governance forums, including current armed conflicts between some member states.

Such tensions create obvious problems for decision-making in forums, which rely on the consensus of all states present. Without downplaying the difficulties of such violent conflicts, we have seen the strong track record of the ATS parties in seizing windows of opportunity for cooperation on the key environmental and resource management challenges for the region. The ATS parties must be ready to act quickly when such windows for cooperation are opening again.

The chapters in this book have demonstrated the climatic and ecological importance of Antarctica for the whole planet. Whilst the ATS has an important role in generating scientific knowledge and political momentum that might be brought into key global forums to manage climate change by reducing emissions, such as the meetings of the United Nations Framework Convention on Climate Change, the Treaty System itself is not set up to reduce global emissions of greenhouse gases. To suggest otherwise would be to burden it with a task that it is unable to fulfil. However, the ATS needs to continue to play a strong role in generating robust and compelling climate-relevant science, clearly expressing the risks of climate change impacts on the region and how regional climate impacts will influence the global climate system. The ATS can also do more in building the resilience of Antarctic ecosystems to climate change impacts by realising more fully the area protection and management mandate of the Madrid Protocol, but this has proven challenging. Finding consensus and realising more fully the area protection and management potential of the ATS, in the face of increasing climate change impacts, is a key challenge.

Antarctica and the Southern Ocean have meant different things to people at different points in time. In this book, Nielsen et al. suggest that it is useful “to think not of one Antarctica, but of many – the region is deeply storied, and these stories accumulate and shift year upon year, much like the ice of the Antarctic continent itself.” There is a growing narrative of Antarctica as embodying an existential threat to communities around the globe – not only impacted by us but also impacting upon us. In this context, melting polar ice is more than a symbol for a planet facing a climate crisis but also increasingly narrated as a central factor in that crisis: a source of catastrophic impacts projected especially for low-lying communities. This narrative highlights global entanglements – as protecting Antarctica becomes about protecting the rest of the world – and is gaining increasing traction in media and in multilateral political discourse. Examples include the Helsinki Declaration at the 2023 Antarctic Treaty Consultative Meeting as well as several intergovernmental cryosphere coalitions, such as the “Ambition on Melting Ice” high-level group led by Chile and Iceland, the “One Planet Polar Summit” high-level effort led by France, and the “Polar Initiative” led by Monaco.

Closing Messages

A recurring theme across many of the aspects discussed here is that, despite their critical importance to the rest of the planet and their marked susceptibility to global change, Antarctica and the Southern Ocean remain significantly undersampled.

This has been the case since Antarctic science began, and it remains a key constraint on better scientific understanding and predicting the future of our planet as a whole. Autonomous and robotic systems, and increasingly capable Earth Observation satellites, will go some way to alleviating this issue, but key domains, such as the ocean interior and abyss, and the vast areas beneath the sea ice and ice sheets, remain data deserts and will do for some time. Priorities for future action include scaling up the *in situ* observing networks, securing their longevity, and broadening their interdisciplinary scope to include a greater breadth of key measurements. In parallel, ensuring the continuity of satellite missions is essential, as is developing new satellite sensor capabilities to generate unique new information on key ongoing and future changes. Collectively, this will require strengthened international cooperation and enhanced coordination of interdisciplinary observing system components, in addition to sustained funding commitments. Nonetheless, increasingly robust, long-duration robotic and remotely-piloted platforms offer great scope for this to be feasible, by driving capability for data generation to transcend what is currently possible, and by allowing human-based sampling and measurement to be targeted where it can have the most impact.

In synergy with these developments, next-generation coupled models of Antarctica and the Southern Ocean, and their global connections, are required. These will span a range of capabilities but will include data-assimilative ice–ocean–atmosphere models that can capitalise on advances in the observing system and process understanding with greater agility than current models. Such models will increasingly need to represent complex elements of the ecosystem, so that biogeochemical and biological carbon cycles can be adequately represented, and climate change impacts on biodiversity be projected and assessed as part of management frameworks. The traditional separation of observations and models will dwindle over time, such that both operate more seamlessly as parts of a cyberinfrastructure environment, thus maximising the usefulness of both and providing optimal outputs and scientific evidence upon which to base policy and management decisions. This will create more opportunities for innovative digital techniques, such as artificial intelligence and machine learning, which are now beginning to revolutionise some aspects of polar science.

Such developments are critical, and there is an urgent need to progress them. Antarctica and the Southern Ocean are increasingly recognised as susceptible to extreme events and the potential passing of tipping points, including major loss of ice sheets with impacts on global sea levels, rapid loss of sea ice, marine and atmospheric heatwaves, and impacts on ecosystems and biodiversity. Such occurrences reinforce the requirement to urgently enhance our understanding of Antarctica and its global connections, and emphasise the need for the science we do (and the way that we do it) to be increasingly capable and agile, creating the information essential to inform policy and governance in both regional and global contexts. By so doing, we can contribute to securing Antarctica and the Southern Ocean, and their critical climatic, biological, societal and cultural benefits, for future generations.

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