Australia’s Antarctic climate science

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Summary

This paper provides a brief synopsis of major elements of Australia’s Antarctic climate science, with a particular focus on the physical climate system. The influence of climate change on Antarctica and the Southern Ocean, and the global impact of changes in the Antarctic region, make this research a critical and central element in Australia’s Antarctic science efforts. Australia recognises that the scale and urgency of the science challenges require strong and active research and logistical collaboration across National Antarctic Programs.

Introduction

Australia has a long history of Antarctic climate and weather research, the latter extending back to the original expeditions in the early 20th Century. Glaciological and atmospheric data sets dating from the establishment of the Australian National Antarctic Research Expedition in 1954provide a baseline for present research. Climate research has become an increasingly important element of the program which has worked strongly into projects of the World Climate Research Program, Scientific Committee on Antarctic Research (SCAR) and contributed to reports of the Intergovernmental Panel on Climate Change (IPCC). The cohesiveness, coordination and impact of Australian climate research benefited from the creation in 1991 of the Antarctic Cooperative Research Centre, later to become the Antarctic Climate and Ecosystems Cooperative Research Centre[[1]](#endnote-1) and, most recently in 2019, the Australian Antarctic Program Partnership (AAPP).

In light of recent IPCC reports[[2]](#endnote-2),[[3]](#endnote-3),[[4]](#endnote-4) and the SCAR Antarctic Climate Change and the Environment report[[5]](#endnote-5), this paper provides a brief synopsis of major elements of climate research in the Australian Antarctic Science Program (AASP). The scope focuses on Australian research on the physical basis of Antarctic and Southern Ocean climate, the aim of which has frequently been expressed as ‘*understanding the role of Antarctica in the global climate system*’. This scope is not intended to conceal the significant, if more widely distributed body of research that deals with climate adaptation and impacts. This critical research connects the physical understanding with the challenges of conservation, management and environmental protection as will be briefly elaborated toward the end of this paper.

The overarching direction for Australian Antarctic research derives from the *Australian Antarctic Strategy and 20 Year Action Plan* and the 2022 Update[[6]](#endnote-6),[[7]](#endnote-7). More detailed direction is provided by a Strategic Science Plan, developed in 2020[[8]](#endnote-8), which includes a major theme of Ice, Ocean and Earth-Systems, within which climate science sits. The Earth-systems approach is a central pillar and the Strategic Science Plan clearly articulates the need for a multi-disciplinary approach. This paper, for convenience, steps through the key physical domains, but it is acknowledged that all of these elements are connected and the research itself works across boundaries and disciplines to explore the Earth system. Antarctic and Southern Ocean climate research also connects with broader climate science, which in the Australian context is delivered through partnerships and collaborations across a range of research institutions and government agencies[[9]](#endnote-9).

The Strategic Science Plan also highlights the importance of international collaboration and research, which has been, and remains, a long-term feature of the Australian Antarctic Program. While Australian research has a strong focus on East Antarctica and the adjacent Southern Ocean, Australia recognizes the importance of integrated circum-Antarctic international research to address the major challenges noted in IPCC and SCAR reports.

The physical climate system – key domains

The Antarctic Ice Sheet

Melt from the Antarctic ice sheet is accelerating, and is projected to contribute tens of centimetres of sea level rise by the end of the 21st Century3. It is also the contribution with the greatest uncertainty and, due to the response time of the large ice sheet, will continue to drive sea level over subsequent centuries. IPCC note this as a ‘deep uncertainty’ and include a low-likelihood, high-impact storyline which could lead to a global mean sea level rise of up to 5 m by 2150.

The profound impacts of even median projected sea level rise and the challenges posed by the uncertainties make study of the ice sheet a critical research element in the AASP. The primary focus for Australian research is the East Antarctic Ice Sheet which has large potential for long-term mass loss from ice retreat into the large and deep Wilkes and Aurora subglacial basins. Despite more than a decade of Australian-led collaborative airborne surveys in East Antarctica, significant gaps remain in knowledge of the bedrock under ice and near-coastal bathymetry; knowledge which is necessary to adequately model the ice sheet and its floating ice-shelf margins.

These fringing ice shelves act as a buttress for the grounded ice sheet behind, slowing the flow of ice from the continent to the ocean. Understanding the response of ice shelves to atmospheric, oceanic and sea ice changes is a major source of uncertainty in projections. Modelling the intrusion of warmer waters and consequent melting of floating ice shelves is impacted by poorly charted bathymetry and the ice sheet retreat itself is affected by relatively small scale and often unresolved bed properties upstream of the grounding lines. The influence of subglacial conditions including bed properties which control how the ice slides and deforms are also typically poorly characterised.

Unsurprisingly, research findings paint a complex picture. A recent review of the East Antarctic Ice Sheet[[10]](#endnote-10) found that after 2100, high-emissions scenarios could lead to several metres of sea-level rise over a few centuries, which could be avoided below 2°C warming, in part due to offsetting increases in snow accumulation. However, a separate study[[11]](#endnote-11) identifies a complex process involving groundwater under retreating ice which acts to lubricate and accelerate discharge, which is not currently included in models.

Australian research planned and underway is addressing these uncertainties to better constrain the rate and contribution of the East Antarctic Ice Sheet to sea level rise and seawater freshening. This research focuses on in situ observations[[12]](#endnote-12), satellite and other remote sensing, process-studies and numerical modelling to capture interactions between ice, ocean and atmosphere. Fieldwork both underway and planned will provide observations for critical regions including Denman Glacier and Shackleton Ice Shelf, conduct dedicated marine science to chart the immediate offshore areas, undertake sediment coring and explore past changes in ocean circulation and sediment deposition. Airborne geophysical surveys will continue to provide data from beneath the ocean, floating ice and ice sheet in critical areas near the grounding line, contributing to initiatives including the SCAR-supported BEDMAP and RINGS projects, and US-led BedMachine project.

To build the necessary international coordination and collaboration to identify and address East Antarctic ice sheet research priorities, Australia recently established a new initiative: REACT (Risk of East Antarctic Collapse and Tipping Points). REACT will undertake a workshop and open science conference within the next 12 months to build the community of experts and end users to drive this work and identify resourcing and logistics requirements.

Sea-ice research

Sea ice is a key component of the global cryosphere, the Antarctic and Southern Ocean environment[[13]](#endnote-13), and is a focus of Australian research.

Sea ice presence, movement, properties, and formation and melt substantially modify the interaction and physical and chemical properties of the ocean and atmosphere. Links and feedbacks between physical, biological and biogeochemical processes also play key roles in this system. Antarctic sea ice is a key habitat and food source for ice-dependent biota ranging from micro-organisms to whales[[14]](#endnote-14). Sea ice is strongly coupled to the ocean and atmosphere (and the ice sheet), and is a sensitive indicator, regulator/moderator and modulator of climate variability and change[[15]](#endnote-15).

Sea-ice changes have serious and wide-ranging consequences for the climate system, affecting low-latitude weather patterns, atmospheric and oceanic properties and circulation, the Southern Ocean’s capacity to moderate climate change by taking up, storing and transporting anthropogenic heat and carbon, and the stability of Antarctic ice shelves and sea-level rise. Sea ice changes also impact the structure, function and health of the Antarctic marine ecosystem, and fisheries (including krill), and human activities including navigation, logistical operations and tourism.

Over the last decade, Antarctic sea-ice coverage has shown abrupt increases in variability and overall decline, and with record lows since 2016. The causes of these changes and the differing regional and seasonal components observed, are uncertain, as are the physical effects (including climate feedbacks) and ecological impacts.

Current climate models do a poor job at simulating observed changes in the mean state and patterns of variability of Antarctic sea ice. This is due to incomplete understanding and parameterization of the sea-ice environment and the complex interactive processes and potential feedback mechanisms involved[[16]](#endnote-16). This leads to low confidence in model projections of future climate and declining sea ice (compared to the Arctic) – a serious ongoing deficiency highlighted by IPCC2,3.

The overarching motivation of ongoing Australian research is to improve the representation of the Antarctic sea-ice system and processes in numerical weather, sea ice, climate and ecosystem models, in order to improve short-term operational forecasting and reduce current low confidence in longer-term predictions (of sea-ice loss over coming decades).

This involves gaining improved mechanistic understanding of the sea-ice environment: the role it plays in climate and ecosystems and the processes involved. Research aims to determine and quantify how, where and why change is occurring and the impacts of this change on the physical, biological and biogeochemical environment.

Australian research will include dedicated collaborative cross-disciplinary experiments in the sea ice zone, both from continental stations and vessels. Plans include targeting the East Antarctic pack ice and the coastal fast-ice zones. This work will make increasing use of autonomous technologies and satellite remote sensing to extend surface observations in space and time. Key work includes development of new and improved means for deriving sea-ice information using remote sensing and associated validation studies.

State-of-the-art technologies on Australia’s new icebreaker *RSV Nuyina* will provide unprecedented new capability for sustained measurement and monitoring of the East Antarctic sea-ice environment (in concert with the ocean and atmosphere). Other key elements are ongoing deployment and maintenance of sea ice buoys (within the International Antarctic Buoy Programme, IABP), the long-term monitoring of coastal fast ice (via the Antarctic Fast Ice Network, AFIN) and repeat acquisition of hourly ship observations within the SCAR Antarctic Sea-Ice Processes and Climate (ASPeCt) program.

Modelling studies are an important aspect of research to synthesize observations and investigate processes. This connects closely with research in the modelling communities that also contribute through the Australian Community Climate and Earth System Simulator-National Research Infrastructure (ACCESS-NRI) and the Centre of Ocean and Sea Ice Modelling in Australia (COSIMA). This and international collaborations are the route for improving incorporation of the Antarctic sea-ice system and processes in climate and forecasting models.

Atmospheric sciences

Study of the high latitude atmosphere is a central element of the Australian Antarctic Science Program. The Antarctic atmosphere connects directly to other parts of the globe, and Antarctica exerts an important influence on weather and climate across the whole Southern Hemisphere. Conversely, tropical and mid-latitude influences manifest over the Antarctic via high-altitude wave trains and atmospheric rivers, which push warm, moist air down toward the frozen continent. The recurrent springtime ozone hole over the Antarctic, which has now occurred for over forty years, has resulted in stronger tropospheric winds over the Southern Ocean, which have limited the climate warming over much of the Antarctic surface. The high-latitude atmosphere responds to changes in sea-ice cover, with a removal of sea-ice allowing heat and moisture transfer between ocean and atmosphere. Snowfall out of the atmosphere directly effects sea-ice surface albedo and mass balance, and snowfall is also a key component of ice sheet mass balance.

Key issues centre around the improvement of atmospheric processes in numerical models to improve weather forecasts and longer-term climate predictions. Improvements in climate models over the southern high latitudes will result in better projections of future precipitation, cloud cover, sea-ice, and ozone recovery, and more generally clearer links across the whole Earth system.

Models continue to show significant surface radiation biases over the Southern Ocean, which is largely due to an incorrect representation of clouds over this region[[17]](#endnote-17). Observations made from surface and ship are beginning to provide the data required to evaluate and improve climate models in this region, via improved representation of cloud, precipitation and aerosol microphysics schemes developed from the collected data[[18]](#endnote-18). These recent field campaigns have begun to illuminate the crucial role emissions from biological organisms have on cloud formation and evolution over the Southern Ocean, yet large gaps in our understanding of these complex processes remain.

Observations of large-scale cloud physical properties, such as rainfall and snowfall rates, liquid water content and ice water content, remain sparse over the region – as are smaller-scale properties including cloud particle sizes and phase, and properties of aerosols.

Models also inadequately represent the influence of small-scale processes including the effect of small-scale atmospheric waves, called gravity waves[[19]](#endnote-19). Accurate representation of these waves is essential to correctly represent temperatures in models throughout the atmospheric column. Model representations of winter temperatures in the stratosphere are often colder than measured. This bias in temperature has an important effect on temperature-dependent chemical reactions in the stratosphere which dictate the size of the Antarctic ozone hole. Observations of these waves throughout the atmospheric column above Davis station are helping address this issue.

Atmospheric research efforts are focussed on using detailed observations of atmospheric phenomena to address long-standing issues within climate and numerical prediction models. Research aims to further develop the cross disciplinary approaches necessary to understand complex links and potential feedbacks with physical and biological systems.

In addition to data from the Davis observatory and other stations, the *RSV Nuyina* will provide significantly enhanced atmospheric observational capability.

These observational capabilities, process studies and model code development, together with the ACCESS-NRI modelling infrastructure provide a pathway to embed improved representation of high-latitude atmospheric processes into climate and weather models.

Southern Ocean and Antarctic seas

The Southern Ocean plays a major role in the climate system, taking up and storing more anthropogenic heat and CO2 than any other latitude band of the ocean. The Southern Ocean also sustains key marine ecosystems and ocean-driven melt of the floating coastal ice shelves, and is strongly influenced by sea ice and its strong seasonal cycle (see above).

Observing and understanding changes in the Southern Ocean is a major challenge and focus for Australia. Any change in the uptake of heat and carbon is profoundly important for the future trajectory of global climate. Sea ice coverage, seasonality and properties, as noted above, is subject to large and poorly understood changes which are intrinsically connected to oceanic processes15. Fresh evidence is emerging that interactions between the ocean, sea ice and melting ice sheets will impact deep ocean circulation[[20]](#endnote-20). The East Antarctic Ice Sheet also appears vulnerable to oceanic heat delivery to ice shelf grounding lines10,[[21]](#endnote-21).

Sustained research from the AAPP and its predecessor the Antarctic Climate and Ecosystems Cooperative Research Centre has shown that the Southern Ocean is becoming fresher, more acidic and less oxygenated, and that these processes are occurring more rapidly than any other ocean.

This research is delivered through integrated physical and biogeochemical observations in the East Antarctic sector of the Southern Ocean, coupled with modelling and synthesis. Ship-based observations, in particular from long-term repeated transects, are complemented by extensive year-round data from autonomous profiling floats and satellite remote sensing[[22]](#endnote-22). Other observational approaches which play an important role particularly in difficult to access ice-covered waters include the use of instrumented seals, airborne deployment of expendable sounders and airborne gravity-derived bathymetry. Australia’s Southern Ocean research is driven by significant collaborations, including AAPP and its partners, the Australian Antarctic Division (AAD), Commonwealth Science and Industrial Research Organisation (CSIRO), the Integrated Marine Observing System (IMOS), as well as the Australian Research Council (ARC) funded centres ACEAS (Australian Centre for Excellence in Antarctic Science) and SAEF (Securing Antarctica’s Environmental Future) and various universities.

As the second largest contributor to the global Argo array, Australian deployments play a key role in monitoring changes in Southern Ocean properties. The unique capabilities of *RSV Nuyina* will provide significant opportunities to access, observe and chart the Southern Ocean and coastal areas. Australia will use this enhanced capability, in conjunction with other vessels and international collaboration, to address critical Southern Ocean research.

Ocean modelling research examining links between deep and upper layers of the ocean and the atmosphere, sea ice and ice shelves is conducted within the AASP and through collaborations in the wider research community[[23]](#endnote-23). Ocean modelling in the Antarctic context also involves addressing the significant challenge posed by the ocean-ice-shelf interface: an active area of research for the program[[24]](#endnote-24),[[25]](#endnote-25).

Climate history

Our understanding of the climate system rests fundamentally on observations of its operation on all timescales, and given the shortness of the instrumental record, this makes proxy climate records highly valuable: particularly for the slower elements of the climate system such as the ice sheet, ocean circulation and coupled geophysical elements. Also, for all elements of the climate system it is important to sample past epochs where boundary conditions were different or when the climate operated outside of currently observed ranges. The Antarctic and adjacent Southern Ocean regions provide unique palaeoclimate archives, from ocean sediments to lacustrine records, geomorphology and ice cores. All of these sources of past climate explorations are included within the AASP.

Ice core records have played a large role in Australian research efforts, with significant contributions from the Law Dome ice core records of greenhouse gases[[26]](#endnote-26) and the high-resolution climate history over recent millennia[[27]](#endnote-27),[[28]](#endnote-28). This work has led to the most detailed record of carbon cycle changes from oceanic and terrestrial sources through the last 2000 years, into the anthropogenic fossil carbon era. It also provides information of direct utility for studying past Australian rainfall variations, due to teleconnections between low and high latitude[[29]](#endnote-29),[[30]](#endnote-30).

Despite the high value of existing climate records, questions remain which are central to understanding the Antarctic elements of the climate system and their hemispheric and global implications. Knowledge of the pre-instrumental variation in almost all aspects of the cryosphere is limited, from past sea-ice extent, atmospheric circulation and climate modes, oceanic circulation, heat and carbon fluxes, ice sheet changes and snowfall. New technology and proxy developments (e.g. mean ocean temperature from noble gases in ice cores), and new records are needed to address these questions.

The major activity for Australian palaeoclimate research over the next several years is the initiative, as part of the multi-national efforts of the International Partnerships in Ice Core Sciences (IPICS), to drill a core in pursuit of the longest possible continuous climate history from Antarctica’s ice sheet. Australia’s ‘Million Year Ice Core’ (MYIC) project at Little Dome C began during the 2022-23 season, and will involve retrieval of a 2800 metre ice core extending back over 1.3 million years. This project, with others underway by European, Japanese and Chinese researchers is designed to deliver the necessary replicated climate histories to answer key questions around the climate system changes known as the Mid-Pleistocene-Transition around a million years ago[[31]](#endnote-31).

In addition to the MYIC project, high-resolution ice core studies continue, based on existing ice and records as well as likely short coring to expand spatial coverage. This is also important for building the spatial record of surface mass balance of the ice sheet. The capability of *RSV Nuyina* for marine sediment coring also provides an additional research tool for understanding the Southern Ocean and Antarctic changes on long timescales.

Looking forward

Decadal plan

The AAD is leading development of a Decadal Plan for the AASP that will provide guidance on the priority science to be conducted over the next 10 years. The aim is to define and direct efforts to deliver an integrated, cost-effective, impactful and scientifically excellent AASP over the next decade. Implementation of this plan over time will acknowledge the significant current science commitments in the program whilst guiding new research into the future. The decadal planning process has sought input from several thematic groups of national experts and will be finalised in coming months following additional consultation with international advisors.

Adaptation and impacts

While this paper has focused on the physical basis of climate change, it must be recognized that research to understand and address climate change *impacts* in and beyond Antarctica and the Southern Ocean is also a central element Australia’s Antarctic and Southern Ocean research. The emphasis on this work is considerable, and growing as the wider implications of climate change for the Antarctic region raise critical questions for the wider Earth system and the protection and conservation of Antarctic terrestrial and marine environments and ecosystems. This long-standing work continues to underpin Australian policy, environmental stewardship and engagement in the Antarctic Treaty system.

Climate change impacts and adaptation studies have long been a part of core AAD research, with fundamental aspects also pursued across the portfolio of university-based projects in the AASP. Formation of Australian Research Council centres such as SAEF and ACEAS has provided further capability in this area. It should also be noted that the AAPP and its predecessors have long included a significant element of ecosystem study: both for the role of ecosystem feedbacks in the climate system and also around ecosystem impacts. Key research findings include identifying ecosystem risks such as the vulnerability of krill in an increasingly acidified ocean[[32]](#endnote-32). In 2022, a flagship project was established at AAD to assess the current status and function of East Antarctica’s krill-based ecosystem and facilitate the assessment of changes to this ecosystem under future climate projections. This will assist in distinguishing fishery impacts from environmental variation and change and provide a foundation for decision-making on conservation and management of the Southern Ocean ecosystem within the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

SAEF provides a relatively new initiative with a strong focus on climate impacts on Antarctica and its biodiversity. Recent studies highlight the impact of climate change on the environment and identify it as the most threatening process to Antarctic biodiversity[[33]](#endnote-33),[[34]](#endnote-34). Clarifying climate-related vulnerability of Antarctic ecosystems and biodiversity, and developing climate resilient conservation planning is a focus of research. This information will guide further development of the Antarctic Protected Areas system and the identification and protection of vulnerable species. ACEAS research also includes effects of East Antarctica’s changes on open water and under ice biogeochemistry and ecology as well as the carbon cycle.

These limited examples provide insight into wider Australian Antarctic climate research.

Programmatic change

Two new initiatives in the science program at AAD will significantly shape the delivery of Australian Antarctic science generally, and climate science in particular. These are the establishment of an East Antarctic Monitoring Program (EAMP) and a new East Antarctic digital platform: Integrated Digital East Antarctica (IDEA).

Observations and monitoring are fundamental elements of a climate research program as noted throughout this paper. The EAMP is presently in a development phase and will provide a structured basis for much of the related climate studies which provide monitoring at the individual research project level. EAMP will commit to sustained observations of essential biodiversity, climate and ocean variables, underpinned by an interdisciplinary, strategically prioritized monitoring plan. Such an integrated and sustained observing system will enable the detection of change at a range of spatial and temporal scales, and with that information, Australia will be much better placed to play a leading role in the management and environmental stewardship of the Antarctic region. The EAMP will also take advantage of technological developments in data science, remote and automated sensors, space-borne instruments, and autonomous vehicles, such as long-range drones, to enhance observations and monitoring.

The AAD plans to work with the national and international Antarctic science communities throughout 2023-24 in the development of the EAMP. Such collaboration will be essential for the detailed design of a successful EAMP, as it will enable knowledge sharing, identification of data gaps around critical variables and processes, and integration of different perspectives and expertise.

The digital platform for East Antarctica, IDEA, is a science program that will facilitate and coordinate the acquisition, integration, analysis, synthesis and delivery of Antarctic and Southern Ocean data and data products. This platform will provide seamless access to multiple and integrated sources of data and data products to underpin science and inform decision making. Importantly, it will facilitate a truly multidisciplinary approach to better understanding the nature, extent and implications of a changing climate on environments and biodiversity in Antarctica and the Southern Ocean.

Concluding remarks

The influence of climate change on Antarctica and the impact of changes in Antarctica and the Southern Ocean on climate make this research a critical and central element in Australia’s Antarctic research efforts. Present research and increases in capability will continue to drive the Australian Antarctic Science Program, in accordance with its strategic framework and through the decadal planning process currently underway. Australia will continue to have a central focus on the Earth system, spanning physical and biophysical aspects of climate change and the understanding of the impacts of climate change in Antarctica and the Southern Ocean for ecosystems and the environment. In its plans for Antarctic operations, policy and science, Australia recognizes the importance of the climate challenge and will focus on key issues. Australia also recognizes that the scale and urgency of the science challenges require strong and active research and logistical collaboration across the National Antarctic Programs.

References

1. . Australian Government Department of Industry, Innovation and Science. 2019. Antarctic Climate & Ecosystems Cooperative Research Centre: 1991-2019. <https://wwwace.aappartnership.org.au/wp-content/uploads/2019/10/ACE-CRC-1991-2019.pdf> [↑](#endnote-ref-1)
2. . IPCC. 2019. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N.M. Weyer (eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. [doi:10.1017/9781009157964](https://doi.org/10.1017/9781009157964). [↑](#endnote-ref-2)
3. . IPCC. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp., [doi:10.1017/9781009157896](https://doi.org/10.1017/9781009157896). [↑](#endnote-ref-3)
4. . IPCC. 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds.). Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., [doi:10.1017/9781009325844](https://doi.org/10.1017/9781009325844). [↑](#endnote-ref-4)
5. . Chown, S.L., Leihy, R.I., Naish, T.R., Brooks, C.M., Convey, P., Henley, B.J., Mackintosh, A.N., Phillips, L.M., Kennicutt, M.C. II and Grant, S.M. (Eds.). 2022. *Antarctic Climate Change and the Environment: A Decadal Synopsis and Recommendations for Action.* Scientific Committee on Antarctic Research, Cambridge, United Kingdom. <https://scar.org/library/scar-publications/occasional-publications/5758-acce-decadal-synopsis/file>. [↑](#endnote-ref-5)
6. . Australian Antarctic Division. 2016. *Australian Antarctic Strategy and 20 Year Action Plan*. <https://www.antarctica.gov.au/site/assets/files/53156/20yearstrategy_final.pdf>. [↑](#endnote-ref-6)
7. . Australian Antarctic Division. 2022. *Australian Antarctic Strategy and 20 Year Action Plan Update* 2022. <https://www.antarctica.gov.au/site/assets/files/53156/2022_update_20yearstrategy.pdf>. [↑](#endnote-ref-7)
8. . Australian Antarctic Division. 2020. *Australian Antarctic Science Strategic Plan.* <https://www.antarctica.gov.au/site/assets/files/53931/australian-antarctic-science-strategic-plan_1.pdf>. [↑](#endnote-ref-8)
9. . Australian Government Department of Climate Change, Energy, the Environment and Water. 2022. *Australia’s 8th National Communication on Climate Change.* [https://unfccc.int/sites/default/files/resource/NatComm8 Biennial Statement\_2022\_v8 21 Dec.pdf](https://unfccc.int/sites/default/files/resource/NatComm8%20Biennial%20Statement_2022_v8%2021%20Dec.pdf). [↑](#endnote-ref-9)
10. . Stokes, C.R., Abram, N.J., Bentley, M.J., Edwards, T.L., England, M.H., Foppert, A., Jamieson, S.S.R., Jones, R.S., King, M.A., Lenaert, J.T.M., Medley, B., Miles, B.W.J. and Coauthors. 2022. Response of the east Antarctic ice sheet to past and future climate change, *Nature*, vol. 608, pp. 275–86, [doi:10.1038/s41586-022-04946-0](https://doi.org/10.1038/s41586-022-04946-0). [↑](#endnote-ref-10)
11. . Li, L., Aitken, A.R.A., Lindsay, M.D. and Kulessa, B. 2022. Sedimentary basins reduce stability of Antarctic ice streams through groundwater feedbacks, *Nature Geoscience*, vol. 15, pp. 645–50, [doi:10.1038/s41561-022-00992-5](https://doi.org/10.1038/s41561-022-00992-5). [↑](#endnote-ref-11)
12. . Cook, S., Nicholls, K., Vaňková, I., Thompson, S., and Galton-Fenzi, B. 2023. Data initiatives for ocean-driven melt of Antarctic ice shelves. *Annals of Glaciology*, 1-6. [doi:10.1017/aog.2023.6](https://doi.org/10.1017/aog.2023.6). [↑](#endnote-ref-12)
13. . Clem, K., R. Massom, S. Stammerjohn, and P. Reid. 2022a. Antarctic Sea Ice #1: Physical Role and Function. SCAR Antarctic Environments Portal. [doi:10.48361/tqhw-c793](https://doi.org/10.48361/tqhw-c793). [↑](#endnote-ref-13)
14. . Clem, K., R. Massom, S. Stammerjohn, and P. Reid. 2022b. Antarctic Sea Ice #2: Biological Importance. SCAR Antarctic Environments Portal. [doi:10.48361/8tky-2793](https://doi.org/10.48361/8tky-2793). [↑](#endnote-ref-14)
15. . Clem, K., Massom, R., Stammerjohn, S. and P. Reid., P. 2022c. Antarctic Sea Ice #3: Trends and Future Projections. SCAR Antarctic Environments Portal. [doi:10.48361/4d9d-1g64](https://doi.org/10.48361/4d9d-1g64). [↑](#endnote-ref-15)
16. . National Academies of Sciences, Engineering, and Medicine. 2017. *Antarctic Sea Ice Variability in the Southern Ocean-Climate System: Proceedings of a Workshop*. Washington, DC: The National Academies Press. [doi:10.17226/24696](https://doi.org/10.17226/24696). [↑](#endnote-ref-16)
17. . Fiddes, S.L., Protat, A., Mallet, M.D., Alexander, S.P. and Woodhouse, M.T. 2022. Southern Ocean cloud and shortwave radiation biases in a nudged climate model simulation: does the model ever get it right? *Atmos. Chem. Phys.,* 22, 14603-14630. [doi:10.5194/acp-22-14603-2022](https://doi.org/10.5194/acp-22-14603-2022). [↑](#endnote-ref-17)
18. . McFarquhar, G.M., Bretherton, C.S., Marchand, R., Protat, A., DeMott, P.J., Alexander, S.P., Roberts, G.C., Twohy, C.H., Toohey, D., Siems, S., Huang, Y., Wood, R. and Coauthors. 2021. Observations of Clouds, Aerosols, Precipitation, and Surface Radiation over the Southern Ocean: An Overview of CAPRICORN, MARCUS, MICRE, and SOCRATES. *Bull. Amer. Meteor. Soc.*, 102, E894–E928, [doi:10.1175/BAMS-D-20-0132.1](https://doi.org/10.1175/BAMS-D-20-0132.1). [↑](#endnote-ref-18)
19. . Alexander, S. P., Orr, A., Webster, S., and Murphy, D. J. 2017. Observations and fine-scale model simulations of gravity waves over Davis, East Antarctica (69°S, 78°E), *J. Geophys. Res. Atmos.*, 122, 7355– 7370, [doi:10.1002/2017JD026615](https://doi.org/10.1002/2017JD026615). [↑](#endnote-ref-19)
20. . Li, Q., England, M.H., Hogg, A.M., Rintoul, S.R. and Morrison, A.K. 2023. Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature* 615, 841–847. [doi:10.1038/s41586-023-05762-w](https://doi.org/10.1038/s41586-023-05762-w). [↑](#endnote-ref-20)
21. . Herraiz-Borreguero, L. and Naveira Garabato, A.C. 2022. Poleward shift of Circumpolar Deep Water threatens the East Antarctic Ice Sheet. *Nat. Clim. Chang*. 12, 728–734. [doi:10.1038/s41558-022-01424-3](https://doi.org/10.1038/s41558-022-01424-3). [↑](#endnote-ref-21)
22. . Newman, L., Heil, P., Trebilco, R., Katsuro, K., Constable, A., van Wijk, E., Assman, K., Beja, J., Bricher, P, Coleman, R., Costa, D., Diggs, S. and Coauthors. 2019. Delivering Sustained, Coordinated, and Integrated Observations of the Southern Ocean for Global Impact. *Frontiers in Marine Science*. 6. [doi:10.3389/fmars.2019.00433](https://doi.org/10.3389/fmars.2019.00433). [↑](#endnote-ref-22)
23. . Huguenin, M.F., Holmes, R.M. and England, M.H. 2022. Drivers and distribution of global ocean heat uptake over the last half century. *Nature Communications* 13, 4921. [doi:10.1038/s41467-022-32540-5](https://doi.org/10.1038/s41467-022-32540-5). [↑](#endnote-ref-23)
24. . Zhao, C., Gladstone, R., Galton-Fenzi, B.K., Gwyther, D., and Hattermann, T. 2022. Evaluation of an emergent feature of sub-shelf melt oscillations from an idealized coupled ice sheet–ocean model using FISOC (v1.1) – ROMSIceShelf (v1.0) – Elmer/Ice (v9.0), *Geosci. Model Dev.*, 15, 5421–5439, [doi:10.5194/gmd-15-5421-2022](https://doi.org/10.5194/gmd-15-5421-2022). [↑](#endnote-ref-24)
25. . Richter, O., Gwyther, D.E., Galton-Fenzi, B.K., and Naughten, K.A. 2022. The Whole Antarctic Ocean Model (WAOM v1.0): development and evaluation, *Geosci. Model Dev.*, 15, 617–647, [doi:10.5194/gmd-15-617-2022](https://doi.org/10.5194/gmd-15-617-2022). [↑](#endnote-ref-25)
26. . Rubino, M., Etheridge, D. M., Thornton, D. P., Howden, R., Allison, C. E., Francey, R. J., Langenfelds, R. L., Steele, L. P., Trudinger, C. M., Spencer, D. A., Curran, M. A. J., van Ommen, T. D., and Smith, A. M. 2019. Revised records of atmospheric trace gases CO2, CH4, N2O, and δ13C-CO2 over the last 2000 years from Law Dome, Antarctica, *Earth Syst. Sci. Data*, 11, 473–492, [doi:10.5194/essd-11-473-2019](https://doi.org/10.5194/essd-11-473-2019). [↑](#endnote-ref-26)
27. . Jong, L. M., Plummer, C. T., Roberts, J. L., Moy, A. D., Curran, M. A. J., Vance, T. R., Pedro, J. B., Long, C. A., Nation, M., Mayewski, P. A., and van Ommen, T. D. 2022. 2000 years of annual ice core data from Law Dome, East Antarctica, *Earth Syst. Sci. Data*, 14, 3313–3328, [doi:10.5194/essd-14-3313-2022](https://doi.org/10.5194/essd-14-3313-2022). [↑](#endnote-ref-27)
28. . PAGES 2k Consortium. 2013. Continental-scale temperature variability during the past two millennia. *Nature Geosci* **6**, 339–346. [doi:10.1038/ngeo1797](https://doi.org/10.1038/ngeo1797). [↑](#endnote-ref-28)
29. . van Ommen, T., Morgan, V. 2010. Snowfall increase in coastal East Antarctica linked with southwest Western Australian drought. *Nature Geosci* 3, 267–272. <https://doi.org/10.1038/ngeo761>. [↑](#endnote-ref-29)
30. . Vance, T.R., Kiem, A.S., Jong, L.M., Roberts, J.L., Plummer, C.T., Moy, A.D., Curran, M.A.J. and van Ommen, T.D. 2022. Pacific decadal variability over the last 2000 years and implications for climatic risk. *Commun Earth Environ* 3, 33. [doi:10.1038/s43247-022-00359-z](https://doi.org/10.1038/s43247-022-00359-z). [↑](#endnote-ref-30)
31. . IPICS. 2020. *White paper - The oldest ice core: A 1.5 million year record of climate and greenhouse gases from Antarctica.* Wolff, E., Brook, E., Dahl-Jensen, D., Fujii, Y., Jouzel, J., Lipenkov, V., Severinghaus, J., Fischer, H., van Ommen, T., Bauska, T. and Higgins, J. (eds.). <https://pastglobalchanges.org/sites/default/files/download/docs/working_groups/ipics/white-papers/ipics_oldaa_final.pdf>. [↑](#endnote-ref-31)
32. . Kawaguchi, S., Ishida, A., King, R., Raymond, B., Waller, N., Constable, A., Nicole, S. Wakita, M. and Ishimatsu, A. 2013. Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nature Clim Change* 3, 843–847 (2013). [doi:10.1038/nclimate1937](https://doi.org/10.1038/nclimate1937). [↑](#endnote-ref-32)
33. . Lee, J., Raymond, B., Bracegirdle, T., Chadès, I., Fuller, R.A., Shaw, J.D. and Terauds, A. 2017. Climate change drives expansion of Antarctic ice-free habitat. *Nature* 547, 49–54 (2017). [doi:10.1038/nature22996](https://doi.org/10.1038/nature22996). [↑](#endnote-ref-33)
34. . Lee, J. R., Terauds, A., Carwardine, J., Shaw, J. D., Fuller, R. A., Possingham, H. P., Chown, S.L., Convey, P., Gilbert, N., Hughes, K.A. McIvor, E., Robinson, S.A. and Coauthors. 2022. Threat management priorities for conserving Antarctic biodiversity. PLoS Biology, 20(12), e3001921. [doi:10.1371/journal.pbio.3001921](https://doi.org/10.1371/journal.pbio.3001921). [↑](#endnote-ref-34)