Chapter 13

The future evolution of Antarctic climate: conclusions and upcoming programmes

Martin Siegert[1], Fabio Florindo[2], Laura De Santis[3] and Tim R. Naish[4]
[1]Grantham Institute and Department of Earth Science and Engineering, Imperial College London, London, United Kingdom, [2]National Institute of Geophysics and Volcanology, Rome, Italy, [3]National Institute of Oceanography and Applied Geophysics – OGS, Sgonico, Italy, [4]Antarctic Research Centre, Victoria University of Wellington, Wellington, New Zealand

13.1 Introduction: the past is key to our future

There is no doubt that the Antarctic ice sheet is experiencing significant mass loss through anthropogenic warming and is contributing to global sea-level rise. The satellite altimetric record of ice-sheet surface-elevation changes reveals a sixfold increase in the rate of loss over the last 30 years (Rignot et al., 2019; Shepherd et al., 2018). Since around 1850 the concentration of atmospheric CO_2 has risen from $\sim$280 to over 415 parts per million (ppm), resulting in a global mean temperature rise of $\sim$0.9°C–1.2°C (IPCC, 2018, 2021; Schurer et al., 2017). While thermal expansion of the ocean has been the dominant process forcing just under half of the $\sim$20 cm of sea level rise since 1850, the contribution of glaciers and ice sheets now exceeds thermal expansion and it is likely to become a growing and controlling component with further warming (IPCC, 2019).

While global warming is undoubtedly the underlying cause of ice-sheet changes measured, the processes by which greenhouse-gas emissions lead to ice-sheet decay are complex, yet critical to evaluating how the ice sheet may change in future. The physical relationships involved are important because they will dictate how the ice sheet is likely to change under further warming, be it constrained to 1.5°C above pre-industrial levels by reducing emissions to net zero by mid Century or driven higher by unabated emissions (Rogelj et al., 2018).

The greatest Antarctic ice loss is being observed within deep-marine terminating margins of West Antarctica (around the Amundsen Sea

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Embayment) and also in parts of East Antarctica (e.g., Totten Glacier; 67°S, 116°E). The main driver for such change is warm ocean water and high-salinity current intrusions that can advect across continental shelves and under cavities below floating ice, up to the ice-sheet grounding zone where the ice-sheet margin is melted (IPCC, 2019). This melting leads to ice-shelf and ice-sheet thinning, and grounding zone retreat. In regions where the bed slopes down towards the ice sheet interior, a runaway process called 'marine ice sheet instability' (MISI) can occur, which is particularly relevant in West Antarctica where the bulk of the ice sheet rests on a bed >1 km below sea level, and some parts of East Antarctica. Indeed, some have argued that MISI is already underway in West Antarctica (Joughin et al., 2014; Rignot et al., 2014).

Although we appreciate the role that ocean warmth is playing on ice-sheet mass balance, the details and processes are not known well enough to allow numerical models to describe observations confidently, or to predict with certainty how the situation will evolve this century (Siegert et al., 2020). Modelling is hampered by insufficient knowledge of (1) the bathymetry around the ice sheet margin, despite it controlling how warm and saline water flows towards the ice sheet; (2) coarseness of resolution, disallowing eddies (despite them being key to the transfer of heat from the ocean to the ice sheet) and surface winds to be accounted for adequately; (3) ocean observations along the ice sheet margin, which could provide valuable information with which to constrain models; and (4) sufficiently detailed records of past change around the Antarctic continental margin explaining how, when and why the Antarctic ice sheet has reacted to periods of global warming. Given the potential consequences for rapid global sea level rise if the West Antarctic Ice Sheet and the marine-based sectors of the East Antarctic Ice Sheet were to become unstable, better definition and measurement of past and modern processes, and their incorporation into models, is critical.

Floating ice shelves are key to changes to the ice sheet upstream, as they offer a 'backforce' against the flow of ice that restricts how much ice can enter the ocean and affect sea-level rise irrespective of whether it melts or not. They are able to receive warmth from both the ocean and the atmosphere, and so may suffer loss of ice from both their upper and lower boundaries. In the Antarctic Peninsula, ice-sheet disintegration has occurred suddenly (Banwell et al., 2013), followed by acceleration of the flow of grounded ice. Under further warming this century (especially in the upper-range of possibilities), the stability of ice shelves becomes questionable. If a large ice shelf suddenly disappears, it is possible that the ice-sheet grounding line becomes a vertical wall of ice. If that wall is unable to support itself mechanically it will fail by calving, leading to migration of the wall, and grounding line, upstream. This is the marine ice cliff instability (MICI) hypothesis and has the potential to cause ice loss much more quickly than through MISI (DeConto and Pollard, 2016; Pattyn et al., 2017).

The drivers for rapid ice-sheet change, and sea-level outcomes, are now clearer. While we must improve our ability to model the processes responsible (Siegert et al., 2020), we also need to look into the palaeo record to observe whether, how and under what conditions such changes have occurred in the past and, especially, if irreversible thresholds in conditions and ice-sheet behaviour have led to inevitable and substantial ice-loss episodes.

Under Hutton's principle of 'uniformitarianism' (Hutton, 1788), past changes can be explained by processes witnessed today. That is to say, past changes – even those in deep time – are caused by physical processes that we can quantify now. Under this principle, physical processes behave regularly and if we understand them well enough they can be used to explain the geological past and what may happen in the future. Hence, understanding of physical processes responsible for ice-sheet events in the geological record is essential for predictions of ice-sheet change this century and beyond.

Irrespective of whether we can constrain greenhouse gas emissions, there are likely to be examples in the palaeo record of what to expect from Antarctica in future. Warming, even under the 1.5°C scenario (Siegert et al., 2019), is inevitable, and substantial change under high emissions remains possible. Resolving which pathway we are on, and the consequences for global sea level, is one of the greatest scientific challenges of the modern age.

Models are needed to make quantitative predictions (Siegert and Golledge, 2021, this volume), and while improvements in their design are necessary so too is better resolution and spatially widespread information of past changes, to a level where physical processes can be deciphered, both locally and regionally (see Colleoni et al., 2021, this volume, for further details). If we can achieve this, models can be better 'trained' against the palaeo record and used with more confidence to make predictions, especially regarding how rates of change are represented in the past and can be replicated plausibly in numerical models.

13.2 Upcoming plans and projects

There is great reason to be optimistic that the next ten years will see knowledge of past changes in Antarctica improve to the extent that it can help predict how physical processes will influence our future. Clearly the global sea-level problem is the central focus of this challenge, but there are also consequences for future ocean conditions and marine life that the palaeo record can inform.

The contribution of the Scientific Committee on Antarctic Research (SCAR) to this challenge, in its promotion of both international collaboration and continental-wide appreciation, should not be underestimated. SCAR's role in forming a scientific Horizon Scan (Kennicutt et al., 2015), where the most important 80 scientific questions that need answers within 20 years were defined, has allowed research proposals to focus on shared and essential research ambitions. This, coupled with the response to the Horizon Scan led by the Council of Managers of National Antarctic Programs (COMNAP), where logistics and facilities planning is aligned against scientific drivers (Kennicutt et al., 2016), means that the scientific community is better connected and set-up to deliver the research outcomes necessary to understand past changes in Antarctica and predict its future. The SCAR Research Program 'Past Antarctic Ice Sheet dynamics' (PAIS) has been addressing one of the six priorities of the Horizon Scan: 'Antarctic ice sheets and sea-level – Understand how, where and why ice sheets lose mass'. Furthermore, PAIS, as well as its predecessors 'Antarctic Climate Evolution' (ACE) and the 'ANTarctic Offshore STRATigraphy project' (ANTOSTRAT), has made considerable efforts to coordinate and stimulate international, multidisciplinary research in line with SCAR's ambition for scientists to work collaboratively on the most important problems. Five years on, great progress has been made in many areas (Kennicutt et al., 2019), but because of the long lead times for deep-field projects, the best work lies ahead in the coming decade.

In terms of projects that are upcoming, and relevant to past Antarctic changes, we can immediately point to INSTANT (INStabilities and Thresholds in ANTarctica), SCAR's research programme that developed from PAIS. Importantly, INSTANT aims to "quantify the Antarctic ice sheet contribution to past and future global sea-level change, from improved understanding of climate, ocean and solid Earth interactions and feedbacks with the ice, so that decision-makers can better anticipate and assess the risk in order to manage and adapt to sea-level rise and evaluate mitigation pathways". It will do this by promoting multidisciplinarity and collaboration, and will focus on research programmes that can make a tangible positive contribution to the aim.

SCAR action and expert groups that are underway, and within the INSTANT remit, include:

- PRAMSO (Paleoclimate Records from the Antarctic Margin and Southern Ocean), which will initiate, promote and coordinate scientific research drilling around the Antarctic margin and the Southern Ocean to obtain past records of ice sheet dynamics and ice sheet ocean interactions that are critical for improving the accuracy and precision of predictions of future changes in global and regional temperatures and sea level rise;
- ADMAP (Antarctic Digital Magnetic Anomaly Project) that will compile and integrate all existing Antarctic near-surface and satellite magnetic anomaly data into a digital database and lead to a better appreciation of tectonic structures and history;
- Bedmap3 (Ice thickness and subglacial topographic model of Antarctica) that will compile ice thickness measurements (that now cover the entire continent without major gaps; Cui et al., 2020) to deliver an updated

account of the bed topography in Antarctica, which is a fundamental boundary condition to numerical ice-sheet models; and

- Antarchitecture (internal structure of ice sheets) – providing the first continental-wide assessment of ice sheet stratigraphy that could provide a novel and important way in which ice flow can be constrained.

  Antarctic RINGS - providing more accurate and complete reference of bed topography and bathymetry of the cavity beneath ice shelves around Antarctica. RINGS will clarify current knowledge gaps at the ice-sheet margin and develop protocols to prioritise and systematically collect, analyse and share comprehensive airborne geophysical measurements from the most vulnerable and data-sparse regions. The aim is constraining the ice sheet subglacial hydrology and geology, ice basal mass balance and discharge from all around Antarctica.

Other international programmes that will likely provide answers to why and how fast Antarctica has changed in the past include the International Thwaites Glacier Collaboration, which will focus on understanding modern processes and past changes in the region that has experienced most ice sheet loss and, indeed, is most vulnerable to both MISI and MICI, potentially this century. To improve our knowledge of ice sheet mass balance, SCAR is supporting collaboration with the World Climate Research Programme (WCRP) named 'ISMASS' (Ice Sheet Mass Balance and Sea Level). SCAR, via INSTANT, is also working in partnership with a range of external programmes on this issue, including WCRP's Climate and Cryosphere (CLiC) project, and the numerical model intercomparison projects ISMIP (for ice sheet models) and MISOMIP (specially for marine-based ice sheets).

In addition, there are numerous drilling programmes that are aiming to acquire records from key positions at the margins especially from the East Antarctic sectors, some of which are still completely unknown. A new generation of challenging, shallow (ice-breaker vessel based) and deep (from floating ice) drilling projects have been proposed during the life span of PAIS to be achieved under the coordination of INSTANT, following the successful ANDRILL, SHALDRILL and MeBo projects (see McKay et al., 2021, this volume for further details). They will allow new geological records to be obtained from other ice proximal and coastal areas, crucially needed to fill the knowledge gap between deep-sea marine and ice-core records. Drilling programs are also planned from the ice shelf, near the present-day grounding line and from the centre of today's ice sheet, including within subglacial lakes at the WAIS ice divide, where ancient sedimentary records are expected from geophysical measurements (Smith et al., 2018). Critically, marine sediments from such locations would prove conclusively the absence of ice and, if they can be dated, will determine the last time when the WAIS decayed.

Large efforts will also need to be dedicated to sea-bed mapping and sub-sea bed geophysical surveys, combined with observations of present-day oceanography and ecosystems, because large areas of the Antarctic margin are still very poorly known, despite their importance for reconstructing the ice sheet evolution.

13.3 Conclusions

Predicting 21st Century sea-level change, with a level of precision useful to decision-makers, is a key scientific challenge of our time. Ice-sheet modelling can be used to calculate the rate of ice loss, but improvements are needed in two main areas. The first is by improvement to the models themselves, through better inclusion of physical processes by glaciological theory, laboratory experiments and measurements of ice, ocean and atmospheric interactions. The second is to 'train' models by matching their performance against records of well-known past changes. While great progress has been made in better defining the main stages of the Antarctic ice sheet's evolution, essential work is now needed to provide ice-sheet models with the well-documented case studies they require.

References

Banwell, A.F., MacAyeal, D.R., Sergienko, O.V., 2013. Breakup of the Larsen B Ice Shelf triggered by chain reaction drainage of supraglacial lakes. Geophysical Research Letters 40, 5872−5876. Available from: https://doi.org/10.1002/2013GL057694.

Colleoni, F., et al., 2021. Past Antarctic ice sheet dynamics (PAIS) and implications for future sea-level change. In: Florindo, F., et al., (Eds.), Antarctic Climate Evolution, second ed. Elsevier (this volume).

Cui, X., Jeofry, H., Greenbaum, J.S., Guo, J., Li, L., Lindzey, L.E., et al., 2020. Bed topography of Princess Elizabeth Land in East Antarctica. Earth System Science Data 12, 2765−2774. Available from: https://doi.org/10.5194/essd-12-2765-2020.

DeConto, R.M., Pollard, D.M., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591−597. Available from: https://doi.org/10.1038/nature17145.

Hutton, J., 1788. Theory of the Earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the globe. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 1 (2), 209−304. Available from: https://doi.org/10.1017/S0080456800029227.

IPCC, 2018. Summary for policymakers. In: Masson-Delmotte, V., et al., (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. World Meteorological Organization, p. 32.

IPCC, 2019. Summary for policymakers. In: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., et al. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Available from: <https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/>.

IPCC, 2021. CLIMATE CHANGE 2021: The Physical Science Basis. Summary for Policymakers. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, August 2021.

Joughin, I., Smith, B.E., Medley, B., 2014. Marine ice sheet collapse potentially under way for the Thwaites Glacier basin, West Antarctica. Science (New York, N.Y.) 344, 735−738. Available from: https://doi.org/10.1126/science.1249055.

Kennicutt, M.C., et al., 2015. A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. Antarctic Science 27, 3−18. Available from: https://doi.org/10.1017/S0954102014000674.

Kennicutt, M.C., et al., 2016. Delivering 21st century Antarctic and Southern Ocean science. Antarctic Science 28, 407−423. Available from: https://doi.org/10.1017/S0954102016000481.

Kennicutt, M.C., et al., 2019. Sustained Antarctic research—a 21st century imperative. One Earth 1, 95−113. Available from: https://doi.org/10.1016/j.oneear.2019.08.014.

McKay, R., et al., 2021. In: Florindo, F., et al., (Eds.), Antarctic Climate Evolution, second ed. Elsevier (this volume).

Pattyn, F., Favier, L., Sun, S., Durand, G., 2017. Progress in numerical modeling of Antarctic ice-sheet dynamics. Current Climate Change Reports 3, 174−184. Available from: https://doi.org/10.1007/s40641-017-0069-7.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., Scheuchl, B., 2014. Widespread, rapid grounding line retreat of pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters 41, 3502−3509. Available from: https://doi.org/10.1002/2014GL060140.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M.J., Morlighem, M., 2019. Four decades of Antarctic Ice Sheet mass balance from 1979−2017. Proceedings of the National Academy of Sciences 116 (4), 1095. Available from: https://doi.org/10.1073/pnas.1812883116.

Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G. et al. 2018. Scenarios towards limiting global mean temperature increase below 1.5°C. Nature Climate Change 8, 325−332. Available from: https://doi.org/10.1038/s41558-018-0091-3.

Schurer, A.P., Mann, M.E., Hawkins, E., Tett, S.F.B., Hegerl, G.C., 2017. Importance of the pre-industrial baseline for likelihood of exceeding Paris goals. Nature Climate Change 7, 563−567. Available from: https://doi.org/10.1038/nclimate3345.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., et al., 2018. Mass balance of the Antarctic ice sheet from 1992 to 2017. Nature 558, 219−222. Available from: https://doi.org/10.1038/s41586-018-0179-y.

Siegert, M.J., Alley, R.B., Rignot, E., Englander, J., Corell, R., 2020. 21st Century sea-level rise could exceed IPCC predictions for strong-warming futures. One Earth 3, 691−703. Available from: https://doi.org/10.1016/j.oneear.2020.11.002.

Siegert, M.J., Atkinson, A., Banwell, A., Brandon, M., Convey, P., Davies, B., et al., 2019. The Antarctic Peninsula under a 1.5°C global warming scenario. Frontiers in Environmental Science 7, 102. Available from: https://doi.org/10.3389/fenvs2019.00102.

Siegert, M.J., Golledge, N.R., 2021. Advances in numerical modelling of the Antarctic ice sheet. In: Florindo, F., et al., (Eds.), Antarctic Climate Evolution, second edition Elsevier (this volume).

Smith, A.M., Woodward, J., Ross, N., Bentley, M.J., Hodgson, D.A., Siegert, M.J., et al., 2018. Evidence for the long-term sedimentary environment in an Antarctic subglacial lake. Earth and Planetary Science Letters 504, 139−151. Available from: https://doi.org/10.1016/j.epsl.2018.10.011.