Understanding Future Sea-level Change Around Antarctica

Understanding Future Sea-level Change Around Antarctica

**Information Paper submitted by SCAR and COMNAP**

Summary

In addition to global consequences related to future sea level change, there will be changes to sea level around the Antarctic continent. This Information Paper outlines the: (1) Challenges in accurately predicting location-specific sea-level change for Antarctica’s coastline; (2) Risks that future sea-level change represents for operations including science support and tourism, coastal infrastructure and assets, heritage sites, specially protected and managed areas, and bioregions; and (3) Future research requirements and recommendations for actions to mitigate the identified risks. This directly contributes to ongoing work to address specific policy and research recommendations presented in the 2022 SCAR Antarctic Climate Change and the Environment (ACCE) Decadal Synopsis Report (Chown et al., 2022). The Antarctic region is a driver and responder to change. A changing Antarctic region has implications for how we operate in, manage and protect the region. Research related to sea-level change is ongoing, but key relevant information is presented here.

* Sea-level change around the Antarctic coastline will vary significantly, especially if more ice mass is lost from a particular region than others (e.g., West Antarctica). Under the highest global carbon-emissions scenarios, and if ‘low-confidence’ ice sheet processes play out, sea-level will ‘likely’ *rise* by as much as ~1.2 m in some regions of Antarctica by the end of the century and *fall* by as much ~2.2 m in other regions at the same time.
* Accurate anticipation of sea-level change for the coastline of Antarctica, and its associated impacts, requires improved location-specific knowledge of (i) changes in vertical land elevation due to Earth processes and ice mass loss; and (ii) changes in sea level elevation due to ice mass loss and associated changes in Earth’s gravitational field and rotation.
* The impacts on Antarctic built infrastructure, operations including science and science support, heritage sites, bioregions, ecosystems and specially protected and managed areas will be complex. Understanding that complexity will depend on accurate knowledge of the rate and direction of future sea-level change.
* Making substantial improvements to current sea-level projections for Antarctic coastlines is included within the work plans for SCAR INSTANT for the period leading up to ATCM XLVI (2024).

ACCE Recommendations

The 2022 SCAR ACCE Decadal Synopsis Report included policy and research recommendations that were presented in ATCMXLIV WP30 rev.1 and ATCMXLIV WP31 rev.1 and recognised in ATCM XLIV Resolution 4 (2022). The information, further work, and recommendations provided in this paper contribute directly to the following ACCE recommendations:

* PR 9: The loss of sea ice, fast ice, and ice shelves [sea-level rise] together with the expansion of ice-free areas on the Antarctic continent and changes to temperatures and precipitation, including extreme weather events, will present new challenges for the management of areas of high human activity in the Antarctic (including where infrastructure and other NAP assets are deployed).
* RR 1: Further support the research required to reduce uncertainty about the future of the region and its impact on the Earth System and to identify commensurate management responses. Integrated, international and targeted long-term monitoring programs and observatories are among the most important for reducing uncertainty and for understanding the likely impacts of mitigation and adaptation responses.
* RR: 4 Determine what the contribution will be of the Antarctic Ice Sheet to future sea level rise and reduce uncertainties in projections of the rate and magnitude of that contribution, and effectively communicate the impacts and risks to stakeholders and users.

Background Information

Our planet is warming. Earth’s average surface temperature has increased by more than one degree Celsius over the past century (Masson-Delmotte et al., 2021) and is on track to exceed 1.5 °C above the pre-industrial average by the early 2030’s (Diffenbaugh & Barnes, 2023; Matthews & Wynes, 2022). This temperature increase has already caused sea level to rise by an average of ~20 cm as warming oceans expand and water from melting glaciers, ice caps and ice sheets flows into the sea (Fox-Kemper et al., 2021; Frederikse et al., 2020). Rising sea levels are already impacting coastal infrastructure and environments around the world and will continue to do so at increasing frequency. Studies that examine the impact of sea level rise and the development adaptation planning and policy action to mitigate these impacts has been a focus across our planet’s populated regions.

For Antarctica, such studies are rare. This lack of data and information on climate change impacts in general, and sea-level rise specifically, is concerning as the Antarctic continent supports critical coastal infrastructure that enables national Antarctic programme activities, is home to unique coastal habitats and bioregions, Antarctic Specially Protected Areas (ASPAs), and HSMs. Efforts to plan for, and adapt to, unavoidable change should be encouraged and these efforts require a sound scientific evidence base.

Accurate estimates of the rate and magnitude of future sea-level rise underpin hazard and risk assessment required for adaptation planning. Such estimates are commonly presented as a set of global-mean sea-level projections and their uncertainties based on carbon emissions pathways. The melting of the world’s glaciers and ice sheets does not produce spatially uniform sea-level rise (Stammer et al., 2013). The exact pattern heavily depends on the geographical distribution and rate of melting ice and consequent vertical land motion and changes in Earth’s gravity and rotation.

Generally speaking, in areas close to melting ice sheets the deviation from a global mean rate is large; sea level will, in fact, fall (Figure 1). In the Antarctic region, this sea level fall could have effects on coastal infrastructure and HSMs, and on near-shore navigation, coastal ecosystems, and sea ice.

Addressing knowledge gaps

Currently there are no robust and spatially comprehensive projections of sea level change for Antarctica. Our aim is to address this knowledge gap through research undertaken under the auspices of the SCAR INStabilities & Thresholds in ANTarctica (INSTANT) Scientific Research Programme (https://www.scar-instant.org). Through collaboration between SCAR and COMNAP, the proposal is for the SCAR INSTANT Programme to lead a project to produce location-specific sea-level projections for Antarctica. Project outcomes can then be used by National Antarctic Programmes and other operators, by the CEP and the ATCMs to assess risk and develop appropriate response measures and protocols.

Current projections of sea level change around Antarctica

The latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR6) contains global, state-of-the-art sea-level projections to the year 2100 and beyond[[1]](#footnote-1) (Fox-Kemper et al., 2021). There is strong spatial variation in sea-level projections around Antarctica. For example, sea level is ‘likely’ to *rise* between 21 and 62 cm near Prydz Bay and *fall* by as much as 80 cm along the Marie Byrd Land Coast by 2100 if global greenhouse gas emissions follow a middle-of-the-road pathway (SSP2-4.5) (Meinshausen et al., 2020). Such spatial variation in sea-level projections is expected because sea-level change is not geographically uniform. As mean global sea level rises, local relative sea level in coastal regions may rise or fall, due to many interdependent factors (e.g., Kopp et al., 2015; Stammer et al., 2013). Spatial variation in sea level change is strongly dependent on where the ice melts, with important consequences for Antarctica’s coastline.

Loss of ice mass from a specific ice sheet, or ice sheet sector, produces a distinct pattern of sea level change know as a ‘sea level fingerprint’. The mass of an ice sheet exerts a gravitational ‘pull’ on the adjacent ocean; melting of the ice sheet decreases that pull and ocean water migrates away from the melting ice sheet margin, resulting in sea-level fall (Figure 1). In the ‘far field’, distant from the melting ice sheet, sea-level rise will exceed the global mean due to this ocean water migration (Clark & Lingle, 1977; Farrell & Clark, 1976). The ‘sea level fingerprint’ computed for rapid uniform melting across the entire West Antarctic Ice Sheet is shown in Figure 2. If the West Antarctic Ice Sheet melted at a rate that raised global sea levels by 1 mm/yr on average, sea-level around all West Antarctica and the Antarctic Peninsula would fall by several mm/yr (areas in red shades), whereas most of the East Antarctic coast would have greater rise than the global mean (areas in blue shades). Thus, a necessary consequence of sea level fingerprints is that much of the Antarctic coastline may experience sea-level fall in the future, not sea-level rise.

Changes in ice sheet mass from a specific ice sheet sector induce vertical motion of the land beneath the ice sheet in a distinct pattern, with maximum uplift typically centred where the largest ice mass loss occurs. This vertical land motion (VLM) in coastal regions strongly influences local relative sea level, either lowering (uplifting coast) or amplifying (subsiding coast) the amount of sea level rise ‘driven’ by climate change (Fig. 1). The methodology applied in IPCC AR6 sea level projections (Garner et al., 2021; Kopp et al., 2023) relied on the availability of multi-decadal tide gauge data to characterize local vertical land motion.

Deployment and operation of tide gauges in Antarctica is challenging due to sea ice interfering with conventional tide gauge operations. Due to this challenge, only two sea level time series data from two tide gauges in Antarctica (both in the northern Antarctic Peninsula region) were used to estimate the local influence of VLM for the entire Antarctic coastline. This lack of spatial coverage limits the accuracy of sea level projections along most of Antarctica’s coastal margin. An alternative means to quantify vertical land motion employs GNSS [GPS] measurements e.g., (Barletta et al., 2018; King et al., 2022; Liu et al., 2018; Nield et al., 2014). Recent progress in GNSS instrument deployment and data sharing yields the direction and magnitude of vertical land motion at ~35 sites within 50-100 km distance of sites where infrastructure, heritage structures, ASPAs or penguin rookeries exist (Figure 3). Rapid uplift is taking place where ice mass is being lost near the Amundsen Embayment and the Antarctic Peninsula. Due to complexities in Earth structure and tectonic influences, some coastal sectors in these regions are moving downward. Similar variation in vertical land motions occur around the coast of East Antarctica, but at lower rates. A much greater number of sea-level projections for Antarctic coastal locations that are constrained by local observations can be produced by including GNSS-derived vertical land motion in the projection methodology (Kopp et al., 2023).

The impact of sea level change around Antarctica

Sea level change around Antarctica has the potential to impact, *inter alia,* infrastructure, HSMs, ASPAs, ASMAs, flora, fauna and coastal bioregions. The assumption that sea level change will be uniform around the Antarctic coastline creates the potential for maladaptation as the impact depends on the rate and magnitude of change and whether sea-level rises or falls.

Regions where sea-level rises will experience:

* more frequent coastal inundation including nuisance flooding;
* more extensive flooding during storm or tsunami events;
* landward shifts in land to sea-ice transition zones;
* salinisation of coastal groundwater systems.

Regions where sea level falls may face the following consequences:

* more difficult, or blocked access to wharves and harbours as coastal waterways shallow, as is anecdotally occurring in Greenland due to ice melting;
* possible changes to tidal resonances, especially in enclosed shallow harbours;
* greater distances (horizontally and vertically) from existing infrastructure to the coast, requiring corrective works to infrastructure;
* ocean-ward shifts in the inter-tidal zone, shallowing of the photic zone, and consequent effects on coastal ecosystems;
* emergence of new islands.

In either case, there is need to update maritime charts to ensure ongoing safe navigation in shallow waters.

Uncertainties in sea-level projections are primarily due to the evolving understanding of ice sheet processes. Management decisions that affect global carbon emissions pathways, require a flexible ‘dynamic’ approach to coastal adaptation (Haasnoot et al., 2021; Lawrence et al., 2018; Toimil et al., 2021; van Alphen et al., 2022). These flexible approaches avoid adaptation solutions that lock-in coastal plans and designs that may create a false sense of security or ultimately prove unnecessary. A similar approach could benefit Antarctica.

Planning for sea-level change in Antarctica – an adaptation example

COMNAP reported in ATCM XLII (2019) IP049 *Modernisation of Antarctic Stations: Survey results* that 73% of national Antarctic programmes were in the planning for or process of modernization of their Antarctic facilities. During such planning, many national Antarctic programmes are considering the impacts to their proposed infrastructure of a changing Antarctic region. Recent work by New Zealand presents one such example (see also New Zealand papers in regards to redevelopment of Scott Base including ATCM XLIV (2022) IP020 *Response to comments on the draft Comprehensive Environmental Evaluation (CEE) for the Scott Base Redevelopment*).

Designers and engineers of the new Scott Base station initially planned to use global mean sea level projections from the IPCC AR5 (Church et al., 2013) to future-proof the design. Following input from the science community, local sea level projections to include estimates of vertical land movement from relatively short tide gauge records, and a range of modelled estimates of land movement due to ice mass change, were generated for Hut Point Peninsula (HPP) (Levy et al., 2020) and used to inform the design process. The site-specific sea-level projections indicated that by 2100, sea level along the coast of HPP might rise by as much as ~100 cm or fall up to ~90 cm (Figure 4). These sea level projections (and the range of possible scenarios) are highly dependent on (1) the ice sheet model(s) used to simulate glacial retreat in Antarctica and Greenland since the Last Glacial Maximum (past ~20 kyrs) and future response to climate change, (2) the model that is used to calculate vertical land motion in response to changes in ice sheet volume, and (3) future carbon emissions. These local sea level projections were also used to assess future tsunami hazard to ensure the new facility is resilient within its design ‘life’ (e.g., Power et al., 2019).

Next steps: Location specific sea level projections for Antarctica

An assessment of the implications associated with sea level change around the Antarctic coastline clearly warrants further exploration as this information is critical to plan for and adapt to the unavoidable impacts of climate change. A substantial step toward robust sea-level projections along the Antarctic coastline is possible through use of these GNSS vertical land motion data and their uncertainties that augment decadal tide gauge data. These additional estimates of local land deformation can be incorporated in the methodology of Kopp et al. (2023).

Making substantial improvements to current sea-level projections for Antarctic coastlines is included within the work plans for SCAR INSTANT for the period leading up to ATCM XLVI (2024). This work will produce new projections of future sea level at locations along the Antarctic coastline where GNSS observations of current vertical land motion are available. Inclusion of these data will reduce the reliance on the very sparse tide gauge records used in IPCC AR6. Despite improvement in vertical land motion measurements by GNSS in Antarctica (Figure 3), there are many locations of National Antarctic Programme facilities, ASPAs, and HSMs (top) and penguin rookeries (bottom) without proximal and/or long-running GNSS instruments (Figure 5). The gaps identified in Figures 3 and 5 can be filled if National Antarctic Programmes fund, establish and maintain a spatially extensive network of observations of vertical land motion (GNSS) and sea level (tide gauges). This is a goal of the SCAR INSTANT programme which includes participants from many national Antarctic programmes.

Conclusions

In summary, as the Antarctic Ice Sheet melts, coastlines near to melting ice may see overall sea-level *fall*. This will depend on the distribution and rate of future ice loss in Antarctica and globally and the properties of the solid Earth, especially beneath Antarctica. New observational constraints on vertical land motion and modified methods in producing sea-level projections utilizing GNSS-derived vertical land motion estimates are required for robust and comprehensive projections of sea level for sites of interest along the Antarctic coastline.

While climate change is not explicitly mentioned in the Protocol on Environmental Protection to the Antarctic Treaty, Parties have a key role to play through the CEP, for example by reporting to the ATCM on the state of the Antarctic environment, considering climate change impacts when reviewing or designating protected areas[[2]](#footnote-2), and in undertaking research to support implementation of the Climate Change Response Work Programme (CCRWP).

This paper suggests that Parties support their National Antarctic Programmes to:

* extend the current critical observational infrastructure – especially the network of long-term continuous geodetic observations (GPS) and tide gauges that provide location-specific time-series of changes in land elevation and sea level.
* facilitate research to improve projections of Antarctic ice mass loss and its regional variability.
* monitor local sea-level and land elevation near identified coastal hazards.
* identify risk and to adapt with urgency to impacts that are now unavoidable.
* adopt a dynamic decision-making approach that provides resilience in response to those unavoidable impacts and that can be updated and modified as new information evolves. This dynamic approach is key because sea-level projections are uncertain, especially beyond 2060–2070.

Acknowledgements

SCAR and COMNAP wish to acknowledge the work as presented in this paper of Matt King (The Australian Centre for Excellence in Antarctic Science/ University of Tasmania) [Matt.King@utas.edu.au](mailto:Matt.King@utas.edu.au); Richard Levy (SCAR INSTANT Theme 3 Co-Leader, GNS Science and Victoria University of Wellington) [r.levy@gns.cri.nz](mailto:r.levy@gns.cri.nz); Terry Wilson (Ohio State University) wilson.43osu@gmail.com; Fraser Morgan (Manaaki Whenua Landcare Research) MorganF@landcareresearch.co.nz; and Tim Naish (SCAR INSTANT Co-Chair, Victoria University of Wellington) [timothy.naish@vuw.ac.nz](mailto:timothy.naish@vuw.ac.nz).

Figures

Escala de tiempo

Descripción generada automáticamente

*Figure 1 (previous page) –* Conceptual diagram showing spatial variability in sea level due to changing ice mass and its effect on gravitational attraction and load on the solid Earth. A large ice sheet depresses the crust on which it sits and attracts water close to its margin – the sea floor rises in response to mantle flow away from the large ice mass forming a forebulge that causes a local decrease in relative sea level. Sea level falls next to a melting/retreating ice sheet (area A – Nunatak/Island) as the gravitational attraction decreases, despite land uplift due to isostatic rebound. Sea level rise occurs in areas where the forebulge subsides (area B – Antarctic Island) and in regions far from the ice sheet margin (area C – for example, a Subantarctic island) due to meltwater flux to the ocean and negligible gravitational attraction.

Diagrama

Descripción generada automáticamente

*Figure 2 –* Sea level fingerprint for uniform melting from the West Antarctic Ice Sheet. Uniform mass gain from increased snowfall would produce the same pattern but with opposite sign. Figure reproduced from (Hay et al., 2017). Inset shows the same result centred at the geographic South Pole, and with an expanded colour scale. Modelled sea level is normalized by global sea level change to show the ‘fingerprint’ of rise/fall attributable to West Antarctic melt.

Map

Description automatically generated

*Figure 3* – Vertical motion of the bedrock land surface measured using GNSS [GPS] instruments. Upward motion is denoted by red arrows, downward motion by blue arrows, and the annual rate of vertical motion is shown by the vector length, with 2 mm/yr scale shown. Velocity solution from Ohio State University; data compilation from the SCAR-GIANT REGAIN analysis; site selection based on proximity (50-100 km) to coastal location of interest and quality and duration of GNSS measurement time series.

Imagen que contiene Diagrama

Descripción generada automáticamente

*Figure 4* – Local sea-level projections for Scott Base (see Levy et al., 2020 for methods). Zero point is 2000 for ‘Kopp 2014’ and ‘Bamber 2019 H’ projections, 1998 for Stocchi LGM-RCP8.5 projection, and the mean annual value for 2003 for the Scott Base tide gauge. Photo at right shows waves breaking over reverse osmosis (RO) water intake at Scott Base. Future sea level rise *or fall* is dependent on our future emissions pathway but any change will affect the RO unit and associated infrastructure.

Mapa

Descripción generada automáticamente

*Figure 5a* – ASPAs (blue circles), National Antarctic Programme facilities (red triangles), Heritage Sites and Monuments (HSMs) (green squares); Figure 5b:Penguin rookeries (yellow diamonds). In both a and b the shapes indicate either a lack of a proximal GNSS station (located within a radius of 50km - West Antarctica, or 100 km - East Antarctica) or have a nearby GNSS station with a time-series that is too short to accurately determine vertical land motion. Note that assessment of quality and fitness of purpose of the existing GNSS records requires further work through SCAR’s INSTANT and GIANT programs and the number of sites without requisite information may change.

References

Barletta, V. R., Bevis, M., Smith, B. E., Wilson, T., Brown, A., Bordoni, A., et al. (2018). Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability. *Science, 360*(6395), 1335-1339.

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 & Grant, S.M. (Eds). 2022. *Antarctic Climate Change and the Environment: A Decadal Synopsis and Recommendations for Action.* SCAR, Cambridge, U.K .https://scar.org/library/scar-publications/occasional-publications/5758-acce-decadal-synopsis/file.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., et al. (2013). Sea Level Change. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung , A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1137-1216): Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clark, J. A., & Lingle, C. S. (1977). Future sea-level changes due to West Antarctic ice sheet fluctuations. *Nature, 269*(5625), 206-209. 10.1038/269206a0.

Diffenbaugh, N. S., & Barnes, E. A. (2023). Data-driven predictions of the time remaining until critical global warming thresholds are reached. *Proceedings of the National Academy of Sciences, 120*(6), e2207183120.

Farrell, W., & Clark, J. A. (1976). On postglacial sea level. *Geophysical Journal International, 46*(3), 647-667.

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., et al. (2021). Ocean, Cryosphere and Sea Level Change. In V. Masson-Delmotte, 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 (Ed.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., et al. (2020). The causes of sea-level rise since 1900. *Nature, 584*(7821), 393-397.

Garner, G. G., T. Hermans, R. E. Kopp, A. B. A. Slangen, T. L. Edwards, A. Levermann, et al. (2021). *IPCC AR6 Sea-Level Rise Projections*. Retrieved from: https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report.

Haasnoot, M., Winter, G., Brown, S., Dawson, R. J., Ward, P. J., & Eilander, D. (2021). Long-term sea-level rise necessitates a commitment to adaptation: A first order assessment. *Climate Risk Management, 34*, 100355.

Hay, C. C., Lau, H. C., Gomez, N., Austermann, J., Powell, E., Mitrovica, J. X., et al. (2017). Sea level fingerprints in a region of complex Earth structure: The case of WAIS. *Journal of Climate, 30*(6), 1881-1892.

Hughes, K. A., Convey, P., & Turner, J. (2021). Developing resilience to climate change impacts in Antarctica: An evaluation of Antarctic Treaty System protected area policy. *Environmental Science & Policy, 124*, 12-22.

King, M. A., Watson, C. S., & White, D. (2022). GPS rates of vertical bedrock motion suggest Late Holocene Ice‐Sheet readvance in a critical sector of East Antarctica. *Geophysical Research Letters, 49*(4), e2021GL097232.

Kopp, R. E., Garner, G. G., Hermans, T. H. J., Jha, S., Kumar, P., Slangen, A. B. A., et al. (2023). The Framework for Assessing Changes To Sea-level (FACTS) v1.0-rc: A platform for characterizing parametric and structural uncertainty in future global, relative, and extreme sea-level change. *EGUsphere, 2023*, 1-34.

Kopp, R. E., Hay, C. C., Little, C. M., & Mitrovica, J. X. (2015). Geographic Variability of Sea-Level Change. *Current Climate Change Reports, 1*(3), 192-204.

Lawrence, J., Bell, R., Blackett, P., Stephens, S., & Allan, S. (2018). National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. *Environmental Science & Policy, 82*, 100-107. https://www.sciencedirect.com/science/article/pii/S1462901117306068

Levy, R., Naish, T., Golledge, N., Bell, R., Stocchi, P., Kopp, R., et al. (2020). Sea-level projections for New Zealand’s Scott Base rebuild. *GNS Science report, 2020/13*, 18.

Liu, B., King, M., & Dai, W. (2018). Common mode error in Antarctic GPS coordinate time-series on its effect on bedrock-uplift estimates. *Geophysical Journal International, 214*(3), 1652-1664.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., et al. (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, 2*.

Matthews, H. D., & Wynes, S. (2022). Current global efforts are insufficient to limit warming to 1.5 C. *Science, 376*(6600), 1404-1409.

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., et al. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev., 13*(8), 3571-3605.

Nield, G. A., Barletta, V. R., Bordoni, A., King, M. A., Whitehouse, P. L., Clarke, P. J., et al. (2014). Rapid bedrock uplift in the Antarctic Peninsula explained by viscoelastic response to recent ice unloading. *Earth and Planetary Science Letters, 397*, 32-41.

Power, W. L., Gusman, A., Wang, X., Lukovic, B., & Black, J. (2019). Pilot tsunami hazard study for Scott Base in Antarctica. *GNS Science Consultancy Report 2019/113.*, 60.

Stammer, D., Cazenave, A., Ponte, R. M., & Tamisiea, M. E. (2013). Causes for Contemporary Regional Sea Level Changes. *Annual Review of Marine Science, 5*(1), 21-46.

Toimil, A., Losada, I. J., Hinkel, J., & Nicholls, R. J. (2021). Using quantitative dynamic adaptive policy pathways to manage climate change-induced coastal erosion. *Climate Risk Management, 33*, 100342.

van Alphen, J., Haasnoot, M., & Diermanse, F. (2022). Uncertain Accelerated Sea-Level Rise, Potential Consequences, and Adaptive Strategies in The Netherlands. *Water, 14*(10), 1527.

1. These data can be accessed via an online tool developed by NASA (<https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool>), which allows users to click on a point anywhere in the ocean to obtain the IPCC sea level projection for that location. [↑](#footnote-ref-1)
2. 17% of the present ASPA management plans consider climate change impacts (Hughes et al., 2021). [↑](#footnote-ref-2)