Policy-relevant science highlights from the Antarctic CORDEX project

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Outline

The Antarctic CORDEX (Coordinated Regional Downscaling Experiment) project was initiated by the World Climate Research Programme[[1]](#footnote-1) (WCRP) to coordinate Regional Climate Modelling (RCM) activities to better understand climate process, their variability, and influence on Antarctica’s sea-ice, ice shelves and ice sheet. Antarctic CORDEX provides a common framework for delivering Regional Climate Model simulations, which are produced by multiple polar climate modelling groups throughout the world

***Summary***

The surface mass balance (SMB) of the Antarctic Ice Sheet (AIS), which is the balance between mass gain from snow and mass loss from surface melt, and directly influences global sea-level, is increasingly being investigated using output from RCMs, and particularly Antarctic CORDEX simulations. [NB. SMB does not include dynamic ice loss from the AIS.]

Antarctic ice shelves (the floating extensions of the ice sheet where glaciers flow into the ocean) have undergone unprecedented thinning and retreat in recent decades, and even collapse in some cases, resulting in acceleration of glacier flow into the ocean and increased rates of ice loss and consequent sea level rise. They lose mass either through basal melt by the warming of the underlying ocean or from above by atmospheric driven melt. The relative role of these processes is critical in projecting future ice shelf loss, and therefore, the dynamic loss of ice into the ocean.

CORDEX model simulations have provided the following insights.

* Compared with observations, models tend to underestimate SMB at the low-elevation coastal regions of Antarctica, as well as some ice shelf locations (especially over the Ross Ice Shelf). (Mottram et al., 2021).
* SMB over the grounded (terrestrial) ice sheet is projected to increase over the 21st century as a result of stronger snowfall, which is strongly correlated with near-surface warming, and only partially offset by enhanced surface melt / run-off. (Kittel et al. 2021).
* This projected increase in SMB is equivalent to a reduction in global sea level of 5.1 ± 1.9 cm in CMIP5-RCP8.5 (Relative Concentration Pathway 8.5) and 6.3 ± 2.0 cm in CMIP6-ssp585 (Shared Socioeconomic Pathways 5-8.5). (Kittel et al. 2021) [NB. In ice sheet models Antarctic SMB increase over the 21st century could even out-pace ice dynamic loss under certain climate scenarios leading to a positive mass balance and reduction in global sea-level rise].
* Melt Potential Index (MPI) is highest for Antarctic Peninsula ice shelves, while the MPI value for Pine Island, West Antarctica is the highest outside of the Antarctic Peninsula and suggests that this ice shelf is vulnerable to extreme surface melt events in addition to the well-known basal melting. (Orr et al., 2023).
* In projections, non-linear growth of surface melt and runoff over ice shelves occurs with increased warming over the 21st century, which lowers SMB and potentially leads to melt-induced hydrofracture of some of the ice shelves, facilitating accelerated glacial discharge of grounded ice and increased rates of sea level rise. (Gilbert and Kittel. 2021).

CORDEX makes the following recommendations:

* Support of targeted observational campaigns focused on poorly understood / observed regions with high-precipitation are crucial to understanding model biases, uncertainties, and improving model estimates of Antarctic Surface Mass Balance.
* Encouragement of national modelling groups to participate in Antarctic CORDEX (see <https://climate-cryosphere.org/antarctic-cordex/>). Contact Dr Andrew Orr ([anmcr@bas.ac.uk](mailto:anmcr@bas.ac.uk)) in the first instance.

Background

Antarctic CORDEX provides a common framework for delivering RCM simulations, which are produced by multiple polar climate modelling groups throughout the world, consisting of a) evaluation experiments for the present-day forced by atmospheric reanalysis data, and b) projection experiments for the 21st century forced by global climate model output. Coordinating these simulations encourages cooperation and knowledge exchange between groups and enables the experiments to be performed with multiple RCMs, which are required to better understand local climate processes, model intercomparison studies, and sources of uncertainties. These simulations are freely available to researchers and regularly used in studies assessing the impact of climate change on Antarctica, in particular by the cryosphere community in order to produce improved understanding of how ice sheets, glaciers, ice shelves, and sea ice respond to climate change. This update on Antarctic CORDEX focuses on some of these recent science highlights.

Recent Science Highlights

The AIS is a significant part of the climate system and a crucial contributor to both present-day and future sea level increases in response to global warming, as it contains enough ice to cause almost 60 m rise in global sea level if it all melted. Current estimates suggest that loss (melting) of ice from the AIS is responsible for around 10% of observed global sea level rise since 1993, and that mass loss is accelerating. A key to understanding recent mass loss (and the stability and evolution of the AIS in general) and improving future mass loss projections is improved knowledge of the SMB of the AIS, which is increasingly being investigated using output from RCMs, and particularly Antarctic CORDEX simulations.

Mottram et al. (2021) used simulations from Antarctic CORDEX from five different RCMs (COSMO-CLM, HIRHAM5, MAR, MetUM, and RACMO) to quantify present-day Antarctic SMB. The range of models in this intercomparison study allowed them to identify sources of disagreement / uncertainty in the range of SMB over Antarctica. They found that between 1987 and 2018 that the ensemble average annual SMB integrated over the whole of the Antarctic ice sheet is 2329 ± 94 Gt yr-1, which compares well with observational-based estimates. However, individual model estimates vary from 1961 ± 70 to 2519 ± 118 Gt yr−1. They found no obvious trends in SMB over the present-day period, which is perhaps related to SMB being highly variable on annual timescales. Evaluating the models against observations of SMB, they found that in general they all tended to underestimate SMB at the low-elevation coastal regions of Antarctica, as well as ice shelf locations (especially over the Ross Ice Shelf). This is likely due to underestimation of the snowfall rate, which is related to errors in the cloud microphysics and precipitations schemes used by the models. They also found that the largest spatial differences between model estimates of SMB are for regions characterised by relatively high precipitation and complex topography, such as the Antarctic Peninsula, West Antarctica, and around the Transantarctic Mountains. Moreover, that models with similar values of SMB integrated over the whole of Antarctica often showed substantial spatial variability at basin scale. By contrast, for high-elevation regions (e.g., on the Antarctic plateau) the model SMB estimates are relatively similar. They concluded that targeted observational campaigns focused on poorly understood / observed regions with high-precipitation are crucial to understanding model biases and uncertainties and improving model estimates of Antarctic SMB.

To investigate the dependence / evolution of Antarctic SMB to future atmospheric warming, Kittel et al. (2021) used Antarctic CORDEX simulations to investigate the sensitivity of SMB estimates from the MAR model to different temperature increases. The simulations involve the MAR model being forced by output from two CMIP5 (fifth phase of the WCRP Coupled Model Intercomparison Project) global climate models and two CMIP6 models over 1981-2100, with statistical extrapolation used to expand the results to the whole CMIP5 and CMIP6 ensembles. The CMIP6 ensemble mean near-surface Antarctic temperature is 1.3°C higher than in CMIP5 by the end of the 21st century, thus enabling the sensitivity to different warmings to be evaluated. Their results show that the SMB over the grounded ice sheet is projected to increase in the future as a result of stronger snowfall, which is strongly correlated with near-surface warming, and only partially offset by enhanced surface melt / run-off. This increase in SMB is equivalent to a reduction in global sea level of 5.1 ± 1.9 cm in CMIP5-RCP8.5 (Relative Concentration Pathway 8.5) and 6.3 ± 2.0 cm in CMIP6-ssp585 (Shared Socioeconomic Pathways 585). By contrast, over ice shelves, higher temperatures in the future are associated with stronger surface melting and run-off, which decreases the SMB more strongly in CMIP6-ssp585 compared to CMIP5-RCP8.5. Additionally, the study shows that the CMIP6 low-emission ssp126 and intermediate-emission ssp245 scenarios project a stabilized SMB gain over the grounded ice sheet by the end of the 21st century (resulting in a lower mitigation to sea level rise than in ssp585) and a close-to-present-equilibrium stable SMB for ice shelves. Future uncertainties in these projections are mainly due to large sensitivities to in the model response to the same greenhouse gas scenario.

The floating ice shelves that fringe around 75% of Antarctica’s coastline play an essential role in controlling Antarctic ice sheet stability by restraining (buttressing) the flow of inland ice into the ocean. However, these ice shelves have undergone unprecedented thinning and shrinking in recent decades, and even collapse in some cases, resulting in acceleration of glacier flow into the ocean and increased rates of ice sheet mass loss and consequent sea level rise. The melting responsible for the thinning of ice shelves can be either from below due to increased incursions of relatively warm water and/or above due to warming air temperatures. In relation to the latter, the presence of substantial surface meltwater ponds is widespread over many Antarctic ice shelves during austral summertime in response to intense or prolonged surface melting. Ensuing vertical fracturing (hydrofracturing) of the ice shelves can occur if the meltwater enters downward and enlarges fractures in the ice, potentially triggering their catastrophic collapse, which has occurred over several ice shelves on the Antarctic Peninsula in recent decades. Moreover, increased summertime atmospheric warming in the coming decades and centuries will likely result in increased surface melt intensities over many Antarctic ice shelves, which is expected to cause more ice shelf collapses like those seen on the Antarctic Peninsula. This could prompt significant dynamic destabilisation/retreat of the Antarctic ice sheet, accelerating ice loss and sea level rise. Understanding the response of ice shelves to air temperatures for both the present-day and future is therefore of crucial importance, and increasingly being investigated using output from Antarctic CORDEX simulations.

To determine which ice shelves are vulnerable to melt-induced hydrofracture, Orr et al. (2023) used near-surface temperature output from 1979/80 to 2018/19 from two Antarctic CORDEX simulations (MetUM and HIRHAM5) to calculate a regional surface “melt potential” index (MPI) over Antarctic ice shelves that describes the frequency (MPI-freq, %) and intensity (MPI-int, K) of daily maximum summer temperatures exceeding a melt threshold of 273.15 (0°C), which is the melting point of snow/ice. Results are based on output from two models to enable model-dependence and consistency to be assessed. The study found that MPI is highest for Antarctic Peninsula ice shelves (MPI-freq 23-35%, MPI-int 1.2-2.1 K), lowest (2-3%, < 0 K) for Ronne-Filchner and Ross ice shelves, and around 10-24% and 0.6-1.7 K for the other West and East Antarctic ice shelves (Figure 1). Some of the highest values of MetUM MPI-int are for George VI (2.1 K), Wilkins (1.5 K), and Larsen C (1.2 K) ice shelves on the Antarctic Peninsula, while the value for Pine Island ice shelf (1.7 K) in West Antarctica is the highest outside of the Antarctic Peninsula and suggests that this ice shelf is vulnerable to extreme surface melt events in addition to the well-known basal melting. Hotspots of MPI are apparent over many ice shelves, which is likely associated with localised warming from important small-scale processes such as katabatic outflows and fohn winds. They also showed that the regional circulation patterns associated with high MPI values over West and East Antarctic ice shelves are remarkably consistent for their respective region but tied to different local and large-scale circulation patterns. In particular, for West Antarctic ice shelves the circulation shows a strong connection with tropical sea-surface temperatures (central tropical Pacific/El Niño activity), while for East Antarctic ice shelves the circulation shows a strong connection with the circumpolar westerlies around Antarctica (Southern Annular Mode pattern).

To investigate the dependence of the SMB of Antarctic ice shelves to future warming (and possible melt-induced hydrofracture), Gilbert and Kittel (2021) used Antarctic CORDEX simulations using the MAR model forced by four CMIP models from 1980-2100 to evaluate the sensitivity of ice shelf SMB to warming of 1.5°C, 2°C, and 4°C above pre-industrial temperatures. They found that non-linear growth in melt and runoff occurs with increased warming, which causes SMB to become less positive with more pronounced warming. Consequently, they suggest that melt-induced hydrofracture of ice shelves may be become more likely in the future with more pronounced warming, which can facilitate accelerated glacial discharge and consequently increased sea level rise. Using runoff and melt as indicators of ice shelf stability / possible melt-induced hydrofracture, they identify Larsen C and Wilkins ice shelves (Antarctic Peninsula), Pine Island ice shelf (West Antarctica), and Shackleton ice shelf (East Antarctica) as being most vulnerable to disintegration at 4°C. However, they find that the ice shelf area of Antarctica that is susceptible to melt-induced collapse by the end of the 21st century is reduced by half for warming of 2°C compared to 4°C.

Further details

Further details are available from the coordinators of Antarctic CORDEX, Dr Andrew Orr at [anmcr@bas.ac.uk](mailto:anmcr@bas.ac.uk) and Dr Chris Kittel at [ckittel@uliege.be](mailto:ckittel@uliege.be) or by going to: <https://climate-cryosphere.org/antarctic-cordex/>.

Selected publications

Gilbert, E., and Kittel, C.: Surface melt and runoff on Antarctic ice shelves at 1.5°C, 2°C, and 4°C of future warming, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2020GL091733>, 2021.

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Diagram, map

Description automatically generated

*Figure 1: Maps of the climatological values of the “melt potential” index (MPI) that describes the frequency (MPI-freq, top) and intensity (MPI-int, bottom) of daily maximum summer temperatures exceeding a temperature/melt threshold of 273.15 K (0°C) from 1979/80 to 2018/19 based on output from MetUM (left) and HIRHAM5 (right) simulations*.

1. The World Climate Research Programme is co-sponsored by WMO, the Intergovernmental Oceanographic Commission of UNESCO, and the International Science Council [↑](#footnote-ref-1)