

SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year 2023

Project Title: Bipolar regional climate projections

Computer Project Account: SPNLBERG

Principal Investigator(s): Dr. Willem Jan van de Berg

Affiliation: Utrecht University
Institute for Marine and Atmospheric Research Utrecht (IMAU)

Name of ECMWF scientist(s) collaborating to the project
(if applicable)

Start date of the project: 1 January 2023

Expected end date: 31 December 2023

Computer resources allocated/used for the current year and the previous one (if applicable)

Please answer for all project resources

| | | Previous year | | Current year | |
|--|----------|------------------|-------------------|------------------|-----------------------|
| | | Allocated | Used | Allocated | Used |
| High Performance Computing Facility | (units) | $200 \cdot 10^6$ | $47,5 \cdot 10^6$ | $200 \cdot 10^6$ | $\sim 100 \cdot 10^6$ |
| Data storage capacity | (Gbytes) | 400.000 | 1.184.501 | 400.000 | 1.520.307 |

Summary of project objectives (10 lines max)

Our group provides high-resolution estimates of the past and projected evolution of the climate, surface mass balance and firn evolution of the Antarctic and Greenland Ice Sheets, as well as the climate of the Arctic region. For these aims, we use the polar adapted regional climate models RACMO, which is hydrostatic, and HCLIM in non-hydrostatic mode, and the firn densification model IMAU-FDM. A detailed motivation of the project objectives and methods applied can be found in the special project application for 2023.

The objectives of the ECMWF budget granted for 2022 are four-fold:

- Extended and renew operational simulations for the Greenland and Antarctic Ice Sheet.
- Create for Antarctica and the Arctic several projection simulations within the framework of the EU project PolarRES.
- Represent the climate of the Antarctic Peninsula and Western Weddell Sea in high detail using HCLIM.
- Finalize projections of the projected evolution of firn of the Greenland and Antarctic Ice Sheets.

Summary of problems encountered (10 lines max)

In 2021, we started with the update of RACMO from version 2.3 to 2.4. The technical aspects of this update appeared to be far more cumbersome than expected, therefore, the expected timeline has not been met. The status and progress are discussed below.

It appeared also more complicated to apply HCLIM for the first time for the Southern Hemisphere and Antarctica.

Summary of plans for the continuation of the project (10 lines max)

With the models now in place, we will start carrying out the planned simulations. This comprise ERA5 driven RACMO simulations for the Arctic, Antarctica and Greenland, followed by the first set of GCM driven projections for the Arctic and Antarctica.

Furthermore, the project of applying HCLIM to the Antarctic Peninsula will be continued.

Plans for 2024 are motivated and described in the special project application for 2024. The primary plan is complete the planned projections by RACMO of the climate of the Arctic and Antarctica. Including projections started in the second half of 2023, we will carry out, for two different scenarios (SSP1-2.6 and SSP3-7.0), and driven by two different Earth System Models, projections (2015-2100) for the Arctic and Antarctica. These projections are part of the Utrecht University contribution to the EU-Horizon 2020 project PolarRES.

List of publications/reports from the project with complete references

The 2022 final report gives a short overview of the publications since 2022 arising from the subsequent ECMWF special projects.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

Regional Climate Modelling

1) Operational RACMO simulations

In 2023, we extended our benchmark simulations with RACMO version 2.3p2, driven by ERA5, for Greenland and its surroundings, at 5.5 km resolution, and Antarctica, at 27 km resolution, into 2023. These benchmark simulations of the climate and surface mass balance, i.e., local surface mass gain or loss of glaciated surfaces by (snow) accumulation, sublimation and melt water runoff, are shared with the community (e.g. van Wessem, van de Berg, and van den Broeke (2023)) and used, for example, to estimate the mass balance of the ice sheets (Otosaka et al. 2023). Due to the short time span of these extensions, several months only, the computational costs of these simulations are low.

Furthermore, we decided to replace our existing benchmark simulation for Greenland. In 2020 we decided to renew only the period after 1990 with a ERA5 driven simulation. In the existing benchmark simulation, which starts in 1958, the first part (1958-1978) is driven by ERA-40 boundaries and the second part (1979-1989) with ERA-Interim boundaries. This choice in 2020, to renew only the latest decades, was motivated by the long memory of firn, inducing that simulations cannot be extended backwards and time and merged, while in 2020 ERA5 boundaries prior 1979 in full vertical resolution were not yet available. Hence, in 2020, replacing the whole benchmark simulation was not possible, however, now it is. We therefore decided to renew our operational RACMO2.3p2 benchmark simulation for Greenland. The new benchmark simulation is started in 1940 and will be run until 2023. This simulation is still ongoing, the results will be discussed in the final report of 2023 of this project.

Finally, in 2022 we carried out a RACMO 2.3p2 simulation on 5.5 km, driven by ERA5, covering the glaciated regions in Patagonia. In 2023, the analysis of this simulation is continued, by applying statistical downscaling of the surface mass balance to a grid at 500 m resolution. The statistical downscaling technique is described in Noël et al. (2016). The downscaled product is currently being evaluated using in-situ (Stakes) and satellite (GRACE) measurements. The preliminary results look promising (Fig. 3) and will be the core of a forthcoming publication.

2) Development of RACMO2.4

The regional climate model RACMO consist of the dynamical core of the regional climate model HiRLAM, the description of physical processes of IFS of the ECMWF, extended with additional parameterizations focusing on the description of glaciated surfaces. The operational version of RACMO, version 2.3p2, uses IFS cycle cy33r1. RACMO2.4, the updated version of RACMO, uses IFS cycle cy47r1. Furthermore, in RACMO2.4 the improved snow and ice albedo scheme, introduced in RACMO2.3p3, and updated blowing snow module, developed in 2022, will be embedded. The upgrade of RACMO to version 2.4 has started in 2021.

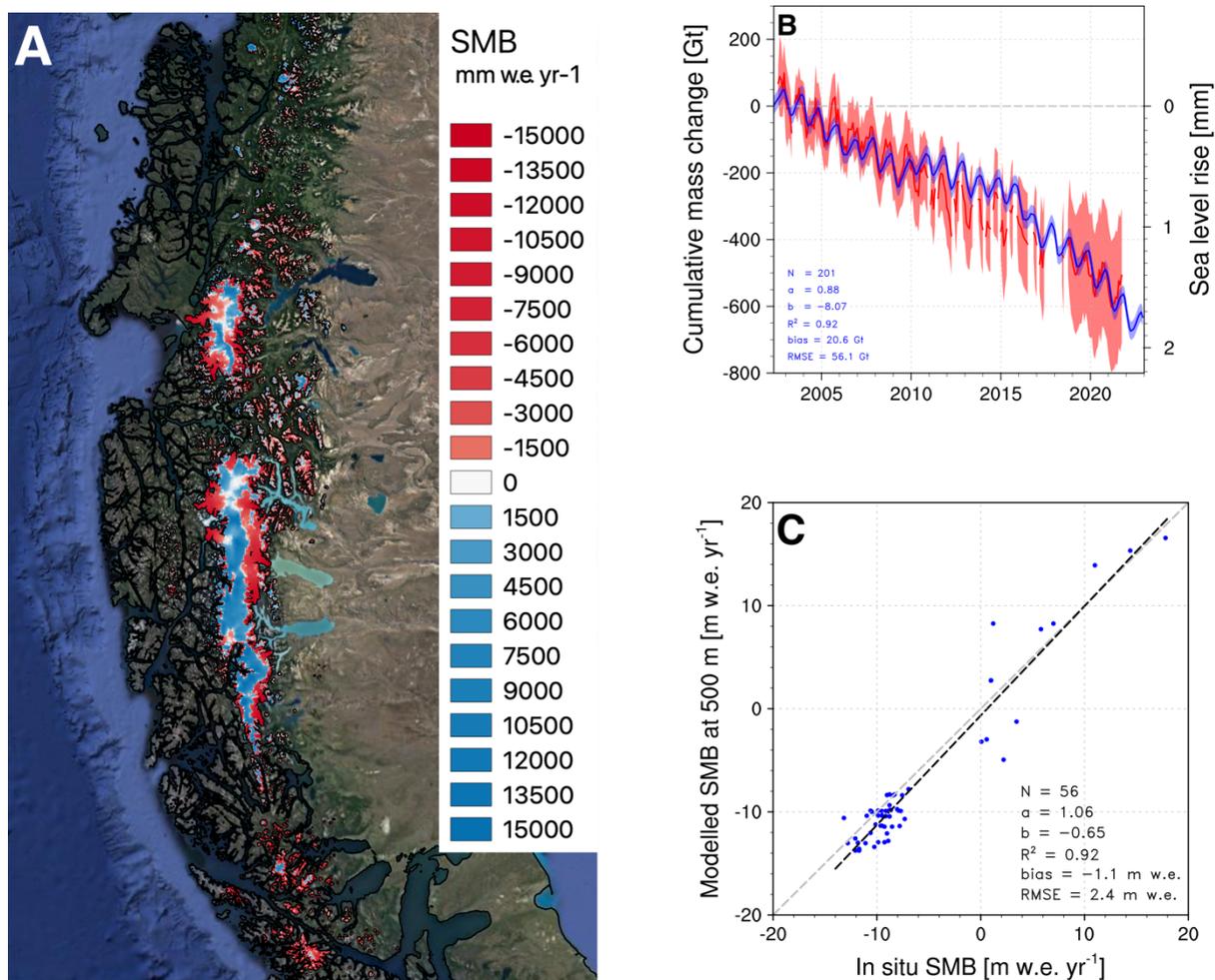


Figure 1: **A)** Annual mean SMB from RACMO2.3p2 at 5.5 km, statistically downscaled to 500 m (1979-2022). **B)** Comparison between modelled (SMB – Discharge, blue) and remotely sensed mass change (GRACE, red) in the period 2003-2022. **C)** Model evaluation using in situ stake measurements.

In 2023, we commenced with more extensive experiments with RACMO2.4 for Greenland, Antarctica, and the Arctic. For example, Figure 2 show the yearly-average total precipitation and surface mass balance of Antarctica for the years 2001-2005. RACMO2.4 runs were carried out on the new 11 km grid. For comparison, these results were regridded to the old 27 km grid to compare with RACMO2.3p3. Previous simulations have shown that the domain extend and resolution impact the modelled integrated precipitation and snowmelt over Antarctica, therefore, we decide to focus directly to the model results on the new planned domain for Antarctica, which necessitate regridding. As its predecessors, RACMO2.4 resembles the known precipitation patterns over Antarctica, with slightly higher precipitation near the escarpment regions of Antarctica compared to the results from the RACMO2.3p3. Consequently, the integrated surface mass balance (Table 1) is also increased compared to the previous version of RACMO. Less snow melt in Antarctica is modelled by RACMO2.4. A part of this decrease introduced by the remapping since melt is mostly concentrated along the edges of the ice sheet. Furthermore, there are differences between the ice masks used in RACMO2.3p3 and RACMO2.4. Still, it clear that in this RACMO2.4 experiment snow melt over the Antarctic ice shelves is underestimated, as RACMO2.3p3 matched snow melt observations well.

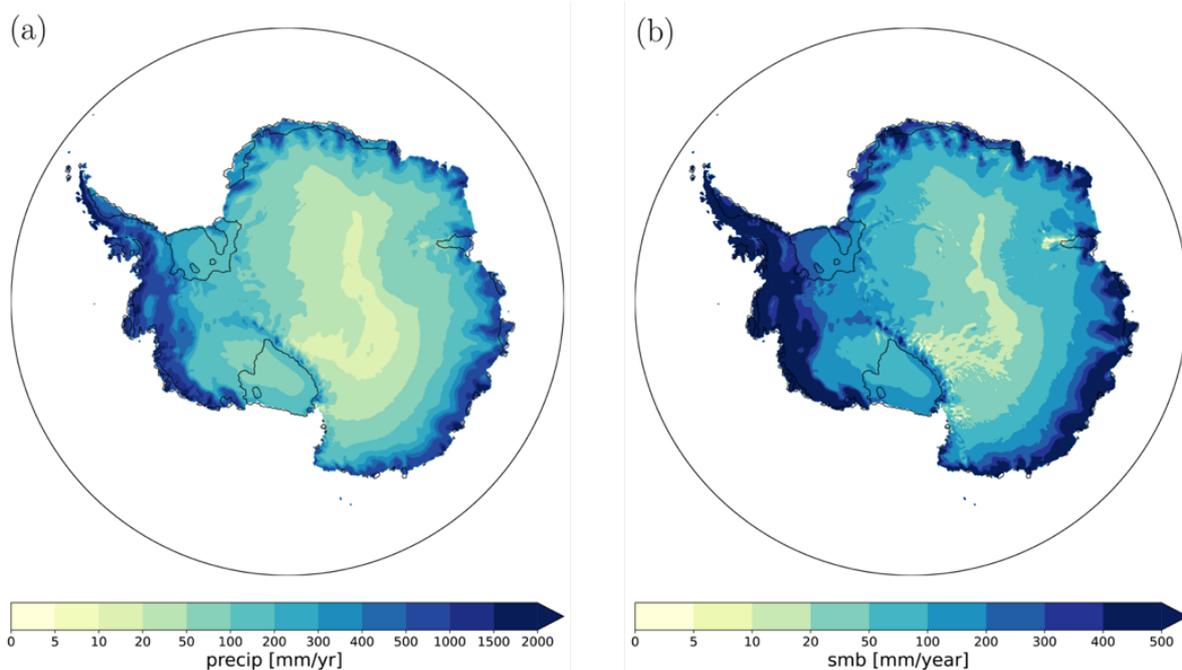


Figure 2: Modelled (a) Total precipitation (mm/yr) and (b) Surface mass balance (mm/yr), both derived with RACMO2.4 using a model resolution of 11 km.

Table 1: Integrated values for the surface mass balance over Antarctica for 2001-2005 along with the total precipitation and melt in Gt (10^{12} kg) per year.

| | RACMO2.3p3 | | RACMO2.4 | | Difference in mean |
|-------------------|------------|----------|----------|----------|--------------------|
| | Mean | σ | Mean | σ | |
| P_{tot} (Gt/yr) | 2707 | 98 | 2831 | 88 | -124 (4.6%) |
| SMB (Gt/yr) | 2496 | 97 | 2611 | 90 | -115 (4.6%) |
| Melt (Gt/yr) | 147 | 35 | 81 | 21 | -66 (44%) |

Similar patterns arose for the Greenland Ice Sheet (GrIS) simulation. Precipitation over the GrIS increases, which can be attributed, for the largest fraction, to the introduced spatial advection of snow. Changing cloud cover and surface conditions cause to lower the modelled melt and subsequent melt water runoff in the ablation zones of the GrIS. As a result, the modelled integrated SMB increased in the initial simulation by about 100 Gt yr^{-1} , where the modelled SMB for these years was typically about 350 Gt yr^{-1} .

Hence tuning was necessary for RACMO2.4 to be able to produce a realistic surface mass balance. In the first half of 2023, numerous short sensitivity tests have been carried out, resulting in selection of tunable parameters. These simulations for Greenland are carried out on a resolution of 11 km to reduce their computational costs. Tuning is applied on the snow albedo (visible light reflectivity) at the transition from a snow-covered surface to bare ice, the fall speed of snow, microphysical processes in mixed phase clouds and the long-wave emissivity of the atmosphere. After this tuning, the SMB components, like melt and precipitation, improve considerably, resulting in a better estimated SMB and smaller differences with the previous RACMO version, RACMO2.3p3 (Fig. 3-left). Still, consistent differences between the two model versions remain. Advection of falling snow across rugged terrain leads to a more spread-out distribution of accumulation, which could increase the agreement of the modelled SMB with observations, which hint that precipitation in RACMO2.3 was too much located in front of topography.

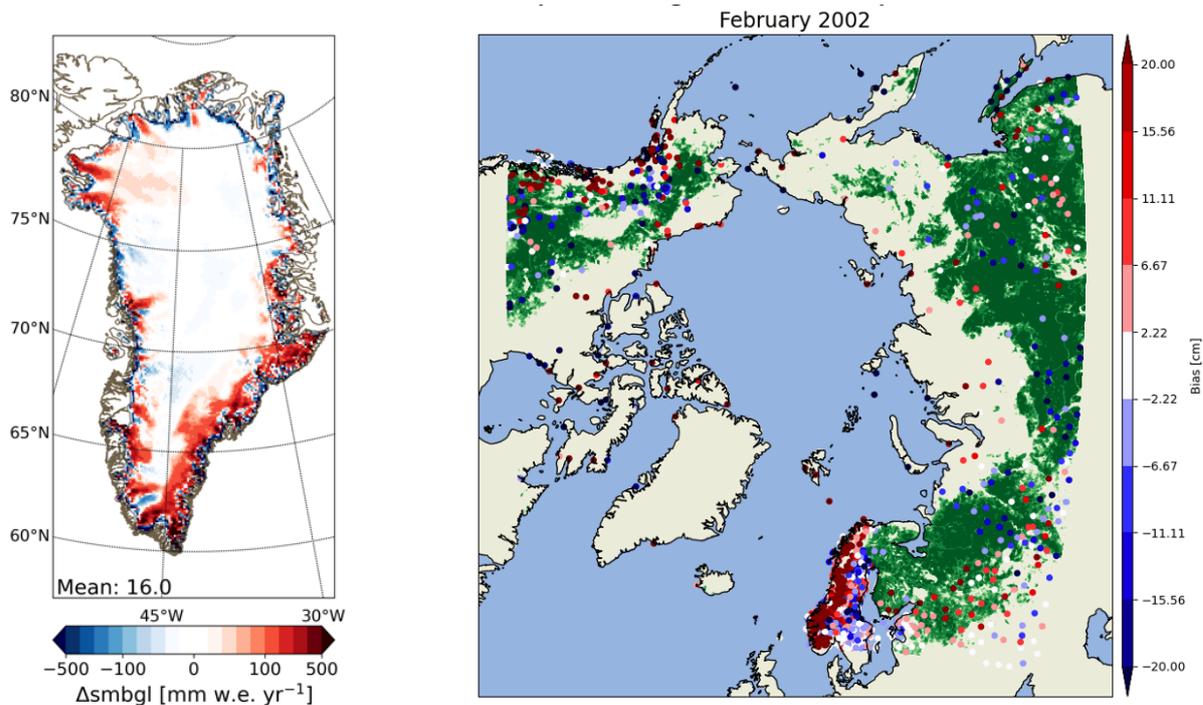


Figure 3: Average yearly surface mass balance difference between RACMO2.4 and RACMO2.3p3, for 2001, for Greenland, using a 11 km resolution grid (left). Modelled snow depth bias compared to observations on the 11 km resolution Arctic domain (right).

Evaluation has also started on the Arctic domain, with an analysis of seasonal snow cover (Fig. 3-right). In general, the 5-layer snow model, which is embedded in the IFS code but not operationally used for ECMWF forecasts, in RACMO only active for non-glaciated land, performs rather well compared to observations. Over mountainous terrains, like Norway, snow cover length and snow depths are systematically overestimated, which indicate that winter snowfall is overestimated, or missing processes, like snow erosion by snow drift, are very relevant here. Elsewhere, winter snow depths match well. In spring, snow disappearance is slightly delayed compared to snow depth observations, gridded observational SWE products, and MODIS albedo measurements. Therefore, a retuning of the snow albedo of snow over non-glaciated land is being tested.

Currently, we are finishing this tuning phase, and finalize the settings for RACMO2.4. From 1 July onwards, we will start longer ERA5 driven reanalysis simulations for all three domains.

3) HCLM

Setting up and testing HCLIM in the Antarctic domain started in August 2022. As HCLIM has never been used in the Southern Hemisphere before, a lot of effort has been directed towards debugging, detecting missing input data, and evaluating performance. The default HCLIM topography datasets GTOPO30 and GMTED2010 were found to poorly represent Antarctica. The first is missing elevation information for ice shelves and the latter has gaps in the elevation data of mountainous regions in the Antarctic Peninsula. HCLIM was therefore set up with a more recent, high-accuracy BedMachine v3 topography and ice mask. HCLIM is now being tested with the Simple Sea-ice Scheme (SICE), and possible nesting and spectral nudging setups.

HCLIM-AROME experiments do show good potential in resolving complex dynamical events, such as the foehn wind event on 27 January 2011 on the Larsen C ice shelf. Foehn events are a common occurrence on the Antarctic Peninsula and can lead to high near-surface air temperature and

surface melt but require km-scale horizontal resolution and non-hydrostatic model dynamics to be accurately simulated in models. The temperature, wind direction and strength of the foehn wind event measured at Institute for Marine and Atmospheric Research Utrecht (IMAU) automatic weather stations 14 and 15 on the Larsen C ice shelf are captured well with the HCLIM-AROME model (see Fig. 4). However, in early 2023, various model biases were detected - for example, HCLIM-AROME runs cannot reproduce high or low-pressure systems entering the Antarctic Peninsula domain, which leads to generally a poor reproduction of surface atmospheric variables. This might come from issues in the retrieval of input boundary conditions from ERA5 but needs further investigation.

Firn Densification modelling

Operational IMAU-FDM simulations

An Antarctic wide simulation with IMAU-FDM v1.2A that covered the period 1979-2021, created in 2021, has been extended to 2022, predominantly to meet the demand of the altimetry community. Details about these simulations are described in the final report of 2021. The model has been updated so that it now writes and reads restart files. Therefore, it is possible continue simulations from the last timestep of a previous simulation, which reduces computational demands for future operational hindcast simulations and projections.

Projections for Antarctica

Continuing the research projected started in 2021, we updated IMAU-FDM to version 1.2AD by implementing a complete transient dynamical firn densification expression, which is needed to capture firn densification accurately in a transient climate. In the updated densification expression, overburden pressure and grain size are taken as state variables, instead of using simplifying assumptions of steady state accumulation and steady grain growth rate.

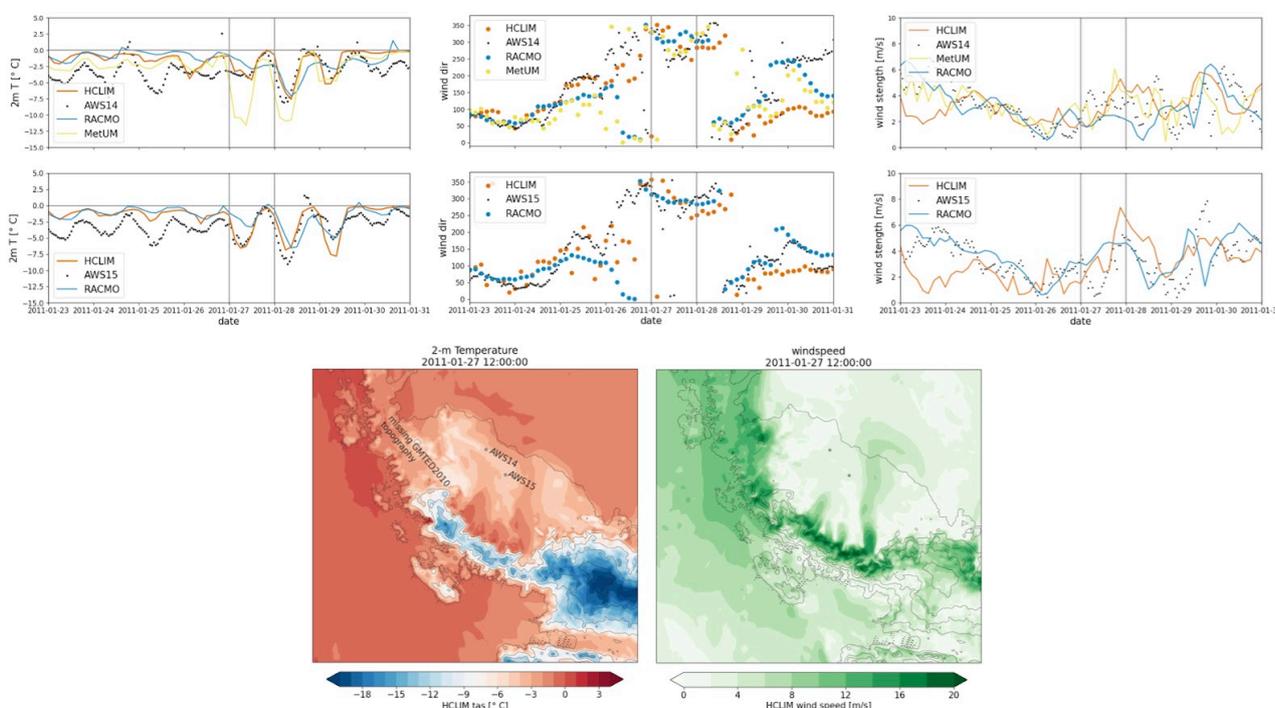


Figure 4: Top row: January 2011 time-series comparison between the observed measurements and output from regional climate models HCLIM-AROME, MetUM and RACMO2p3. From left to right: 2m temperature, wind direction and wind strength. Bottom: HCLIM 2m temperature and wind speed fields for 27th January 2011 at noon.

We evaluated and compared this updated model version 1.2AD against in-situ firn core density measurements and previous model versions using a simulation forced by RACMO2.3p2, in turn driven by ERA5 boundaries. Next, Antarctic wide simulations of the firn evolution till 2100 under various emission pathways using IMAU-FDM v1.2AD have been carried out. These simulations are forced by RACMO2.3p2, driven by CESM2 boundaries, for the scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5. These IMAU-FDM runs are used to project future firn air content (FAC), the total pore space in the firn, which is a measure of the meltwater buffering capacity of the firn. This is especially important for the Antarctic ice shelves as meltwater saturation and ponding can promote ice shelf disintegration.

Figures 5 a,b and c shows the relative total FAC change by 2090-2100 compared to 2005-2014. Over the grounded ice we find regions with increasing or decreasing FAC. On average, FAC for the grounded ice shelves decreases with 0.7%, 1.2% and 2.4% for scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5, respectively. We find decreasing FAC for most ice shelves under all scenarios. Increasing melt rates causes the formation of thick near-surface ice layers >3 m, which can impede vertical meltwater percolation to deeper firn, which limits the ability of the firn to refreeze meltwater. Therefore, we calculate the reachable firn air content, i. e. the firn air content that is reachable for meltwater. For this, we use ice layer thickness to estimate the permeability of ice slabs. Figures 5 d, e and f show the relative change in reachable firn air content by 2090-2100 compared to 2005-2014. The reachable firn air content is derived by estimating the impermeability of ice layers. Especially for SSP5-8.5 the depletion of the reachable firn air content is accelerated compared to the total firn air content, e.g., on relatively dry and cool ice shelves, such as Amery, Shackleton, Ronne-Filchner and Riiser-Larsen.

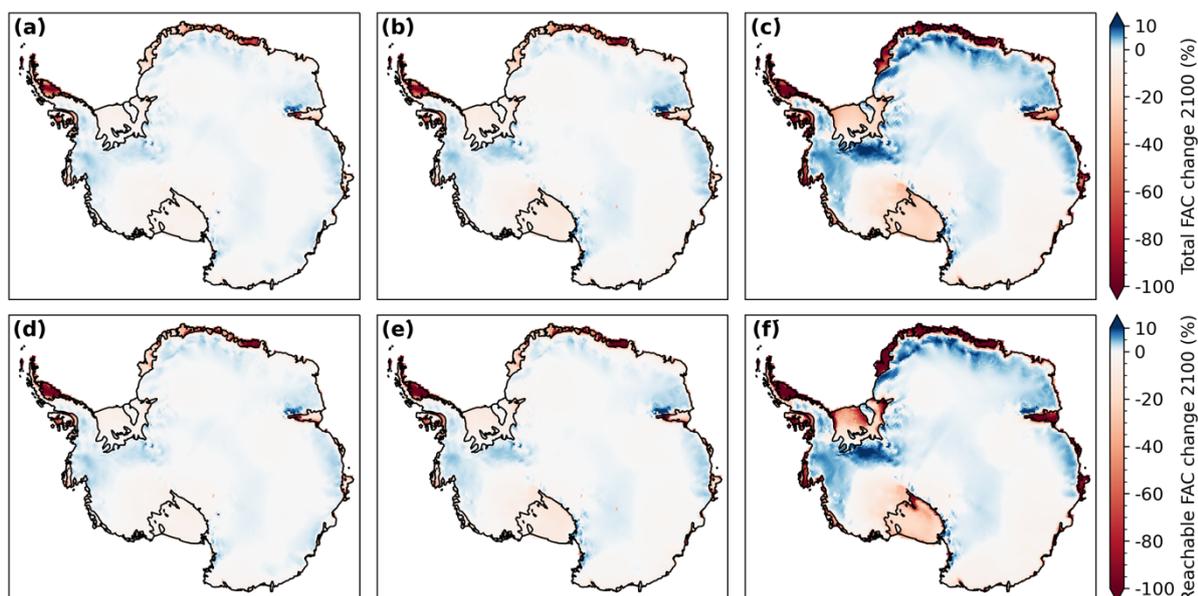


Figure 5. Relative change in total firn air content (FAC) (top row) and relative change in reachable FAC (bottom row) by 2090-2100 compared to 2005-2014 for (a,d) SSP1-2.6, (b,e) SSP2-4.5 and (c,f) SSP5-8.5 compared to 2005-2014.

References

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- Otosaka, I. N., A. Shepherd, E. R. Ivins, N. J. Schlegel, C. Amory, M. R. van den Broeke, M. Horwath, I. Joughin, M. D. King, G. Krinner, S. Nowicki, A. J. Payne, E. Rignot, T. Scambos, K. M. Simon, B. E. Smith, L. S. Sørensen, I. Velicogna, P. L. Whitehouse, G. A. C. Agosta, A. P. Ahlstrøm, A. Blazquez, W. Colgan, M. E. Engdahl, X. Fettweis, R. Forsberg, H. Gallée, A. Gardner, L. Gilbert, N. Gourmelen, A. Groh, B. C. Gunter, C. Harig, V. Helm, S. A. Khan, C. Kittel, H. Konrad, P. L. Langen, B. S. Lecavalier, C. C. Liang, B. D. Loomis, M. McMillan, D. Melini, S. H. Mernild, R. Mottram, J. Mouginot, J. Nilsson, B. Noël, M. E. Pattle, W. R. Peltier, N. Pie, M. Roca, I. Sasgen, H. V. Save, K. W. Seo, B. Scheuchl, E. J. O. Schrama, L. Schröder, S. B. Simonsen, T. Slater, G. Spada, T. C. Sutterley, B. D. Vishwakarma, J. M. van Wessem, D. Wiese, W. van der Wal, and B. Wouters. 2023. 'Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020', *Earth Syst. Sci. Data*, 15: 1597-616.
- van Wessem, J. M., W. J. van de Berg, and M. R. van den Broeke. 2023. "Data set: Monthly averaged RACMO2.3p2 variables; Antarctica." In. 10.5281/zenodo.7760490.