SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Storylines of changing polar climates
Computer Project Account:	spnlberg
Start Year - End Year :	2024-2024
Principal Investigator(s)	Dr. Willem Jan van de Berg
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The following should cover the entire project duration.

Summary of project objectives

This project aims to improve our understanding of the Arctic and Antarctic historical and projected climate as well as evolution of the firn layer, and subsequently the surface mass balance, of the Greenland and Antarctic Ice Sheet. A wealth of data is already provided by atmospheric reanalyses, like ERA5, and Earth System Models (ESMs), but both lack resolution, especially ESMs, and dedicated parameterizations to describe, for example, the snowpack of an ice sheet, in sufficient detail. Therefore, we use the polar adapted regional atmospheric model RACMO, as well as HCLIM with polar modifications. Furthermore, we refine the description of the surface snow layer of ice sheets with the firn densification model IMAU-FDM.

In 2024, our primary focus of the simulations is of the projected climate of the Arctic and Antarctica for different storylines using RACMO.

Summary of problems encountered

No significant problems were encountered. The only minor issue we encountered is that of the thousands and thousands of files we store on ECFS, once a while one or two got corrupted and lost.

Experience with the Special Project framework

The application procedure and reporting procedure is clear.

Summary of results

Before we discuss the numerical experiments carried out in 2024 using the SPNLBERG budget, the three models used for these simulations are introduced.

RACMO

The regional atmospheric climate model RACMO combines the semi-lagrangian semi-implicit hydrostatic core of the former HIRLAM model (Undén et al., 2002, chapter 5) and ECMWF IFS description of physical processes. To represent the near and subsurface processes over glaciated surface more accurate, we developed a polar version of RACMO in which, for example, a new tile representing glaciated surfaces is introduced. This tile models a firn/ice column, and it includes detailed descriptions of snow metamorphism, melt water processes, grain side dependent albedo schemes, and snow drift. In 2024, RACMO version 2.3p2 was used (Noël et al., 2018; van Wessem et al., 2018), which is based on IFS cycle 33r1, and RACMO version 2.4p1 (van Dalum et al., 2024), using IFS cycle 47r1.

HCLIM

For the HCLIM simulations presented here, HCLIM43-AROME23 is used (Belušić et al., 2020), including the simple sea-ice model SICE (Batrak, 2021). HCLIM is the regional climate version of the numerical weather prediction model system ALADIN-HIRLAM, while HCLIM43-AROME23 is the convection permitting configuration of HCLIM. In 2023 and 2024, we implemented several modifications the atmospheric surface and boundary layer schemes to better represent Antarctic conditions by HCLIM and SICE.

IMAU-FDM

To improve predictions of the firn column evolution of the Greenland and Antarctic ice sheet, the 1-D firn lagrangian densification model IMAU-FDM is used (Brils et al., 2022; Veldhuijsen et al., 2023). IMAU-FDM has refined descriptions of firn processes compared to the firn column model in RACMO, employs more and finer layers and is run to steady state for a reference period, most of the time of the last decades of the 20th century. It aims to model accurately the surface elevation evolution and melt water retention capacity of firn.

Proposed simulations and work carried out

For 2024, we proposed 6 experiments to be carried out within the SPNLBERG project. We will discuss these experiments one by one.

1. ***Extend our operational estimates of the climate, surface mass balance and firn state of the Antarctic (11 km resolution) and Greenland (5.5 km resolution) ice sheets into 2024 using RACMO2.4p1 and IMAU-FDM.***

These simulations have been carried out as planned. Next to the simulations mentioned in the proposal, we extended the RACMO2.3p2 simulation for Greenland to 2024. These simulations are relatively computational low cost as only a limited number of months needs to be run for these simulation extensions. Data from these simulations is shared internationally, for example to the IMBIE mass balance intercomparison effort (Otosaka et al., 2023).

Next to these operational simulations, we started working on the comparison of RACMO2.4p1 with EarthCARE satellite observations to evaluate clouds and radiation. The EarthCARE satellite, launched May 2024, aims to measure clouds and aerosols in unprecedented precision and detail (Wehr et al., 2023). From surface observations, we concluded that RACMO2.4p1 has a bias in the longwave downwelling radiation, which likely has to do with biases in the representation of clouds and/or aerosols (van Dalum et al., 2024). For the model evaluation, we extended the RACMO2.4p1 simulation of the Greenland domain at 5.5 km until the end of 2024. For a like-to-like comparison, we adjusted the RACMO output stream to be able to write output on the time step closest to the satellite overpass, specifically for cloud and atmospheric variables on the 40 vertical levels. Code was written to easily compare an EarthCARE overpass with the co-located RACMO profiles. The EarthCARE observations are upscaled to the RACMO grid resolution to be able to make a point-by-point comparison. Using a small set of the first available EarthCARE data frames, a first comparison between RACMO and EarthCARE observations was made.

2. ***HCLIM43 runs at 2 km resolution covering the Antarctic Peninsula and the adjacent western part of the Weddell Sea, to test the sensitivity of the model results to snow albedo, clouds, and aerosol settings.***

For these simulations HARMONIE Climate cycle 43 (HCLIM) was used with the non-hydrostatic HARMONIE-AROME physics package over various Antarctic domains using a high 2.5 km grid spacing. For all simulations, ERA5 reanalysis served as atmospheric forcing at the lateral boundaries. The main aim of the simulations was to assess the default snow model, ISBA-ES, in detail. These simulations are already described in the SPNLBERG ECMWF progress report for 2024. These simulations were used in Verro et al. (2025), in which is showed that the default sea ice snow albedo parameterization of HCLIM is not suitable to describe the sea ice albedo of Antarctica accurately.

Further tests and development with HCLIM have been carried out, concentrating on land snow. Figure 1a-c shows the modelled land albedo over the Queen Maude Land domain, compared to the modelled land albedo from the regional climate model RACMO2.4p1. For these simulations, HCLIM is run with default snow settings, in which albedo is calculated as function of the snow grain size. HCLIM, however, does not model the snow grain size prognostically, but parameterizes the snow grain size from the snow density. Although the spatial variability is more-or-less right, the albedo is largely underestimated over the Antarctic ice shelves, which leads to unrealistically high melt rates and hence unsuitable results.

Figure 1d-e shows the same region and modelling period, but with HCLIM using an updated snow grain size distribution as function of the snow density, which modifies the snow albedo. This albedo update led to a much higher snow albedo but also resulted in less spatial variability. Despite of introducing a low bias over the Antarctic escarpment zone, the biases have significantly reduced over the ice shelves.

Figure 2 shows the 2-m temperature comparisons with measurements from automatic weather stations over the region, with HCLIM default grain size-density relation, and the updated grain size-density relation, respectively. HCLIM went from a warm bias of 1.3 K to a cold bias of -0.7 K, while the RMSE increased from 2.3 to 2.5 K, both because of this update. These experiments led to the conclusion that HCLIM snow albedo scheme, even when updated, is too simplistic to represent Antarctic conditions, as the snow albedo is a function of snow density only in ISBA-ES.

Therefore, a start has been made to enable the CROCUS snow model within HCLIM. CROCUS models a firn column in more vertical and physical detail than ISBA-ES. For example, it includes a prognostic evolution of the snow grain size. The CROCUS code is already embedded in HCLIM but the two-way coupling was not set up. This work, to couple, test and evaluate CROCUS within HCLIM, is still in progress.

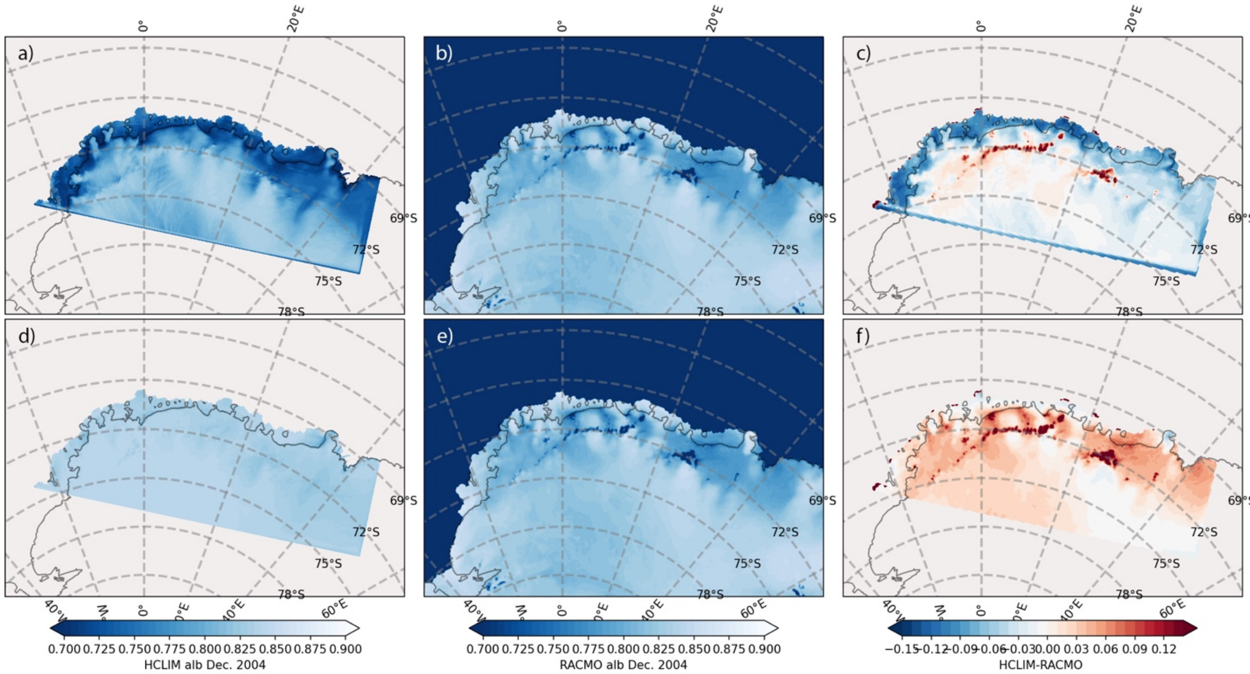

Figure 1: Modelled land albedo for December 2024 by a) HCLIM with default parameterizations, b,e) RACMO2.4p1, and d) HCLIM with updated parameterizations. c) and f) show the differences in modelled land albedo between HCLIM and RACMO2.4p1.

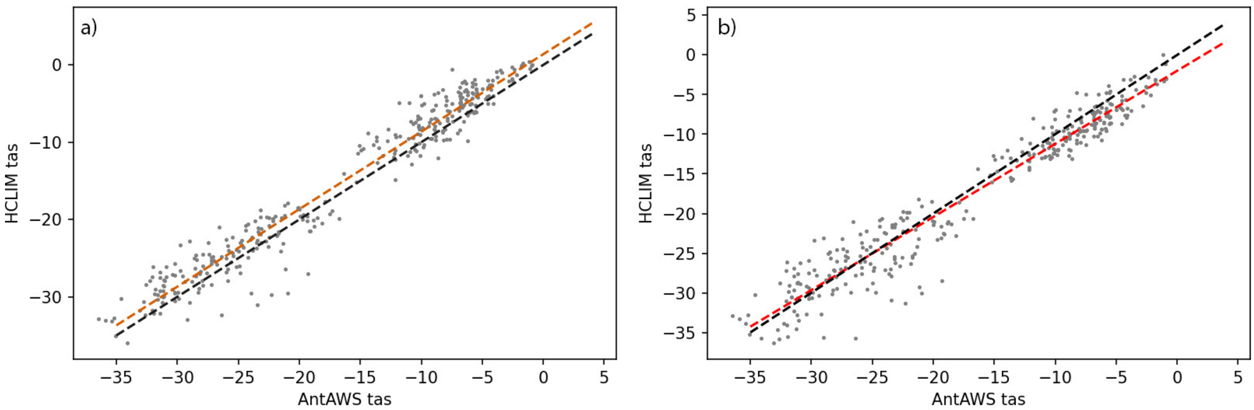

Figure 2: Comparison of the modelled 2 m temperature for December 2024 by HCLIM against in situ observations from the AntAWS dataset (Wang et al., 2023), with for a) using the default albedo parameterization, and for b) using the updated albedo parameterization.

3. ***Continuation of a CMIP6 driven projection for SSP3-7.0 until 2100 for both the Antarctic and Arctic at a resolution of 11 km, using RACMO2.4. These simulations will be commenced in 2023.***
4. ***Another projection for SSP3-7.0 till 2100 for both the Antarctic and Arctic at a resolution of 11 km, using RACMO2.4, using a different CMIP6 ESM than for experiment 1.***

As part of our commitment to the EU-funded H2020 project PolarRES, we conducted these two projections for Antarctica and these two projections for the Arctic. In these simulations we use the newest RACMO2.4p1 version to downscale two CMIP6 Earth Sytem Model (ESM) simulations for each domain that were selected based on a storyline approach. The two simulations of each domain represent two opposing but plausible pathways for either Antarctica or the Arctic. For Antarctica, the storylines differ in the amount of summer sea ice loss and in the delay of the breakdown of the stratospheric polar vortex. For the Arctic, they differ in the strength of the Arctic (warming) amplification and amount of sea ice loss in the Barentz and Kara Seas. All simulations were completed on 11 km resolution, both for the historical period (1985-2014) to allow for evaluation of RACMO forced by ESM as well as projections (2015-2100), using SSP3-7.0 scenario.

It was planned that these simulations were commenced in 2023, but due to technical complications to prepare the ESM data to drive RACMO2.4p1 they were all run and completed in 2024. As these simulations consumed, as projected, most of the requested budget, but were not started in 2023, a budget extension was needed and granted in the fall of 2024.

A publication on the performance of RACMO2.4p1 forced by ERA5 over Antarctica is currently in review (van Dalum et al., 2025), showing that the updated RACMO2.4p1 performs well, better than the preceding RACMO version, in simulating Antarctica's surface mass balance, temperature, albedo, and shortwave radiation, while longwave radiation and turbulent fluxes remain areas needing further improvement. A similar publication for RACMO2.4p1 forced by ERA5 over Greenland is in draft and will be submitted for review later in 2025.

Within the PolarRES framework, these RACMO projections, along with the projections using other regional atmospheric and coupled models, are analysed and used for publication by members of the PolarRES consortium. Furthermore, these RACMO projections for the Arctic and Antarctica will be published on an ESGF server later in 2025. It is thus expected that the data of these simulations will be used in several papers. Here, we discuss only the analysis carried out in our research group.

To build confidence in using RACMO driven by ESM output for projecting Antarctica's future climate and mass balance, we first evaluate its performance by comparing ESM-forced historical simulations to those forced with ERA5 data. Table 1 shows that the average climate and mass balance in summer in the historical period is very comparable between the simulations forced by ERA5 and forced by the ESMs. RACMO(CESM2) is slightly colder and therefore experiences less melt compared to RACMO(ERA5).

We use the future projections to investigate surface melt on Antarctic ice shelves, as meltwater can trigger hydrofracture, leading to ice shelf collapse and contributing to sea level rise. Figure 3 shows again the good agreement between the three simulations in the historical period in terms of temperature and melt, which gives confidence to use these simulations over the 21st century. While no trends are visible in the historical period, apart from a slight decrease in melt on the Antarctic Peninsula (Fig. 3d), all ice shelves are projected to have significant warming and a significant increase in surface melt over the 21st century. In the RACMO(CESM2) simulation this increase in both temperature and melt is consistently stronger compared to RACMO(MPI-ESM).

The downscaled projections with RACMO allow us to study trends in melt as well as drivers of melt. We find a strong link between temperature and melt both in the historical and future simulations, but this relationship is non-linear and differs between regions (Fig. 4). Ice shelves in drier areas (e.g. Amery) melt more at the same temperatures compared to regions experiencing more snowfall (e.g. Nickerson, Larsen C), which can be explained by snowfall regulating the strength of the snowmelt-albedo feedback that causes strong increase in melt. A more in-depth analysis of this non-linear temperature–melt relationship and its drivers will be discussed in a forthcoming publication.

Besides this research, we are currently studying the modelled changes in atmospheric rivers in the Arctic in the RACMO2.4p1 projection simulations as well as the other PolarRES simulations. This research has not led to publishable results yet.

5.

6. ***Three long (1950-2300) transient simulations for Antarctica using RACMO2.4 at 27 km resolution to study the potential for rapid transitions in firn demise.***

Due to the delays in the PolarRES projections discussed above, and other unexpected personal issues, we lacked the manpower to carry out these experiments. Therefore, these experiments, which are part of the EU H2020 OCEAN:ICE project, are postponed to 2025.

Table 1 RACMO2.4p1 simulated summer averages (1985-2014) forced by ERA5, CESM2 and MPI-ESM. The table shows 30-year mean values and standard deviations for ice sheet average near-surface air temperature, surface energy balance [W/m2] and ice sheet integrated mass balance components [Gt/yr] for DJF.

	RACMO(ERA5)	**RACMO(CESM2)**	**RACMO(MPI-ESM)**
T_{2m} [°C]	-23.2 ± 0.8	-24.0 ± 0.6	-23.8 ± 0.6
SW_{in} [W/m^2]	349.6 ± 1.9	350.5 ± 1.4	348.6 ± 2.0
LW_{in} [W/m^2]	155.1 ± 2.5	151.4 ± 1.9	154.4 ± 2.0
SW_{net} [W/m^2]	58.4 ± 0.9	57.9 ± 1.3	56.6 ± 1.0
LW_{net} [W/m^2]	-63.7 ± 0.9	-63.9 ± 0.8	-62.3 ± 0.9
SH [W/m^2]	9.6 ± 0.5	10.2 ± 0.6	9.9 ± 0.3
LH [W/m^2]	-1.9 ± 0.1	-1.8 ± 0.1	-1.9 ± 0.2
Precipitation [Gt]	574 ± 64	566 ± 69	618 ± 46
Surface sublimation [Gt]	-71.2 ± 5.5	-68.4 ± 5.6	-72.7 ± 6.1
Snowdrift sublimation [Gt]	-24.9 ± 3.8	-28.4 ± 4.2	-27.7 ± 2.5
Melt [Gt]	120 ± 38	76 ± 25	126 ± 42
Refreezing [Gt]	113 ± 37	70 ± 26	119 ± 39
Runoff [Gt]	6.3 ± 3.5	6.5 ± 4.0	8.2 ± 3.1
SMB [Gt]	466 ± 63	463 ± 67	509 ± 47

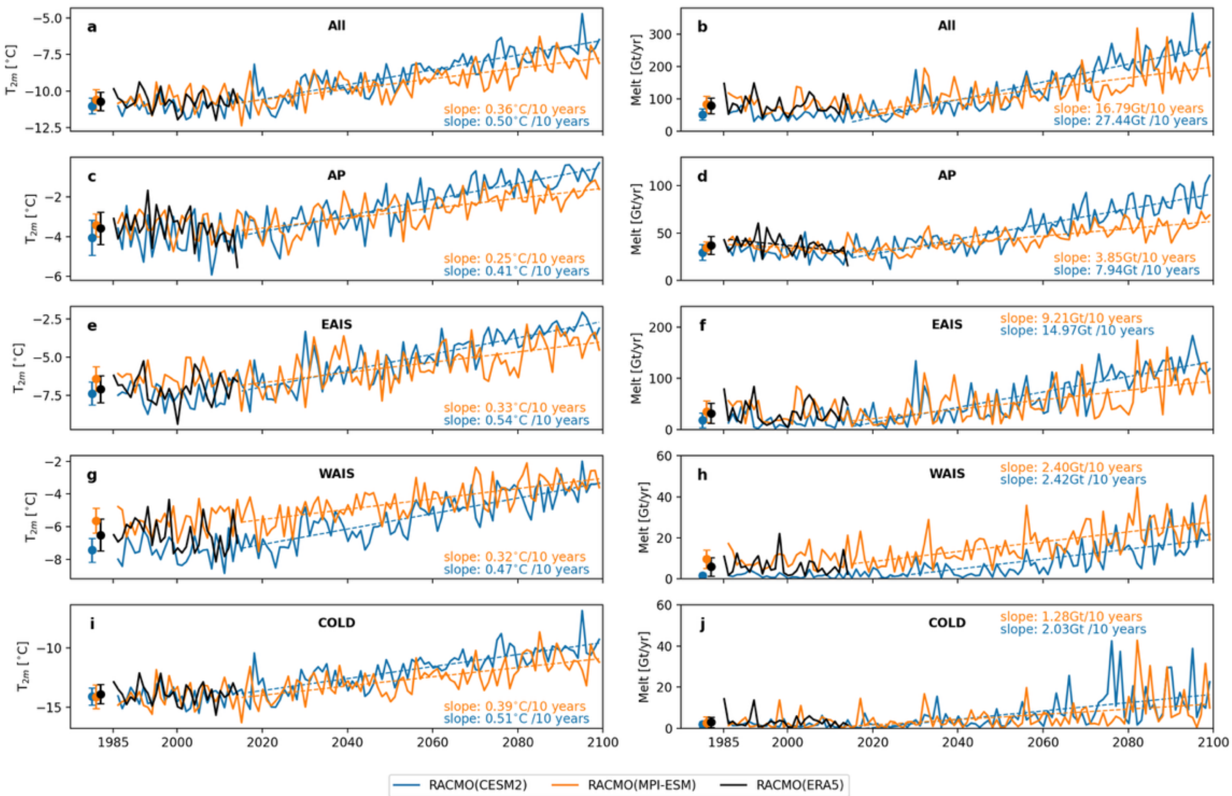

Figure 3: Timeseries of summer average 2m air temperature and melt over all ice shelves and subgroups of ice shelves Antarctic Peninsula (AP), East Antarctica (EAIS), West Antarctica (WAIS), and the Filchner-Ronne and Ross Ice Shelves (COLD). Error bars indicate the mean and standard deviation over the historical period (1985–2014). Trendlines are shown where a significant trend (p-value < 0.05) is detected in either the historical (1985–2014) or future (2015–2099) simulations.

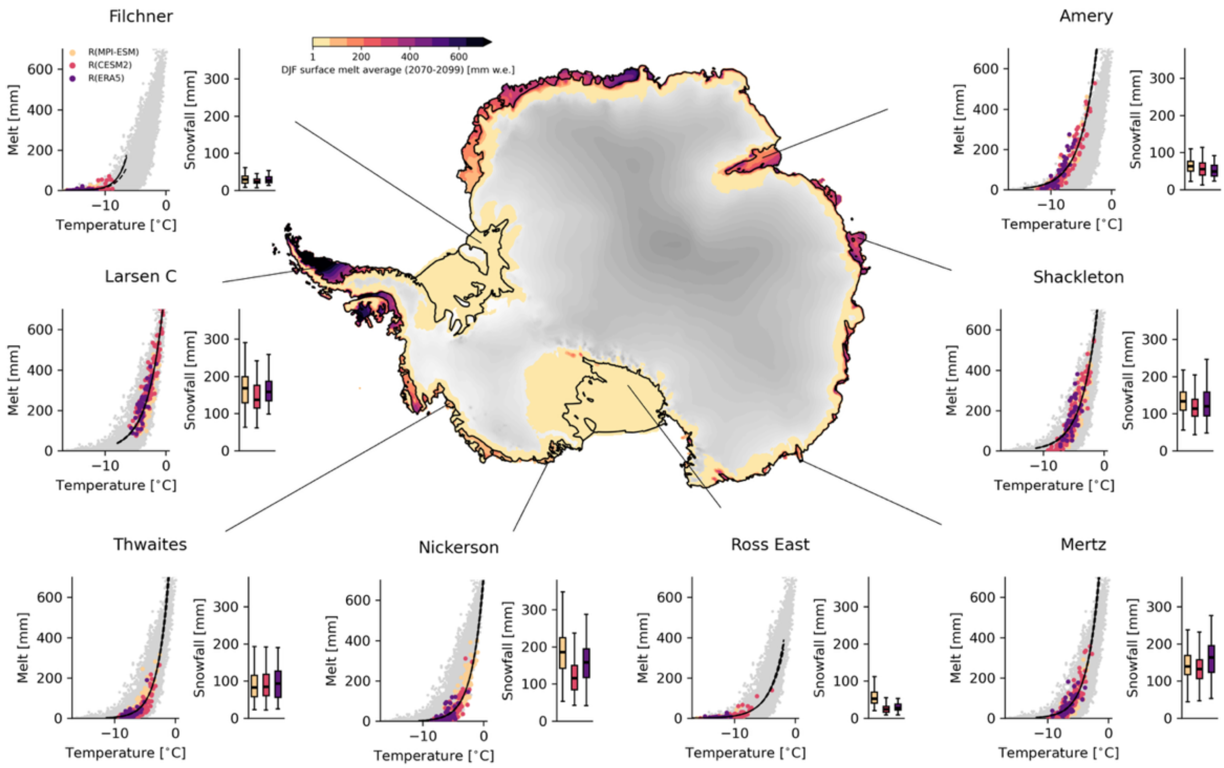

Figure 4: Scatter plots of summer melt vs. temperature from RACMO simulations forced by ERA5 (1979–2022, purple), CESM2 (1985–2099, pink), and MPI-ESM (1985–2099, yellow); grey background shows all ice shelves. Boxplots indicate summer snowfall rates. The map shows average melt for 2070–2099 from RACMO(CESM2), over a grey elevation map of Antarctica.

6. Project the evolution of the Greenland ice sheet firn layer ice sheet until 2100 using IMAU-FDM.

It was planned to carry out these projections of the firn evolution of the Greenland Ice Sheet, similar to those for the Antarctic Ice Sheet, which were not foreseen in the project proposal but carried out in the first half of 2024, as reported in the 2024 SPNLBERG progress report. However, in the course of 2024 it became clear that more model development on IMAU-FDM was needed before these simulations of the Greenland Ice Sheet could be carried out. This model development concerns the parameterization of firn densification for transient climatic conditions, which is not represented well by IMAU-FDM for the climate conditions typical for Greenland.

Furthermore, the existing IMAU-FDM results, created in 2023 and early 2024, were used to train a XGBoost based emulator to predict current and future perennial firn aquifers (PFAs) in Antarctica. PFAs are year-round bodies of liquid water within firn, which modulate meltwater runoff to crevasses, potentially impacting ice-shelf and ice-sheet stability. An emulator cannot outperform the model it is trained on, however, as it uses reduced input data and needs a fraction of the computational costs, this PFA emulator can be applied on data from multiple Antarctica regional climate models, driven by several ESMs. The emulated future PFA distributions vary greatly among the regional climate models as well as driving ESMs, indicating that there is considerable uncertainty in the future occurrence of PFAs. For the strong mitigation scenario (SSP1-2.6), PFA remain confined to the Antarctic Peninsula, however, for strong warming scenario (SSP5-8.5), PFA could (transiently) occur on several Antarctic ice shelves as long as snowfall on the location is considerable, thus more than 500 mm yr^{-1}. These results are presented in Veldhuijsen et al. (2024).

A similar effort has carried out to emulate the total firn air content using XGBoost. The results are promising but require more analysis before publication in a scientific journal. Nonetheless, there are discussed in the PhD thesis of Sanne Veldhuijsen (Veldhuijsen, 2025, chapter 5).

List of publications/reports from the project with complete references

Here are only listed publications mentioned in this report. There are also numerous publications using data generated using SPNLBERG budgets from preceding years, especially from other research groups that use our data, and it is hard to track them all.

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Future plans

Our plans for 2025 are described in the SPNLBERG project proposal for 2025, and an update of their realization is provided in the 2025 progress report. Our plans for 2026 are described in the SPNLBERG project proposal for 2026.

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