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	2025
Project Title:	Modelling polar ice sheet climates at UU/IMAU
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)	N/A
Start date of the project:	1 January 2025
Expected end date:	31 December 2025

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)	230.000.000	208.853.808	130.000.000	10.896.928[a]
Data storage capacity	(Gbytes)	400.000	3.686.991	400.000	2.113.418

[a] As of 20 June 2025.

Summary of project objectives

The SPNLBERG budget supports the polar regional climate and firn modelling group for the research to the climate and snow surface research of the Antarctic and Greenland ice sheets. The budget is firstly used to update operational products of the Antarctic and Greenland climate and surface mass balance. Secondly, it supports model development and the test simulations required for that. Lastly, it provides the budget for the longer dedicated simulations.

Summary of problems encountered

Few technical problems were encountered so far. However, due to changes in personal, we had to reschedule our plans for 2025, and therefore we focussed in the past months on the data analysis of the simulations carried out in 2024 and on model development. As a result, only a fraction of the granted HPCF budget has been consumed so far.

Summary of plans for the continuation of the project

In the remainder of 2025, we plan to catch up on the planned work and carry out the experiments that were proposed for this year. The exception is the proposed HCLIM simulations. The researcher responsible for these simulations left our group earlier than planned, and subsequently this research project with HCLIM is terminated earlier than planned.
Our plans for 2026 are described in the SPNLBERG project proposal for 2026.

List of publications/reports from the project with complete references

No publications or reports have been published so far.

Summary of results

In our project proposal for 2025, we requested budget for 5 experiments. We discuss these one by one below.

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 2025 using RACMO2 forced by the ERA5 reanalysis.*

In the first half of 2025, the operational simulation of RACMO (using version 2.4p1) for Antarctica has been extended from 1 January 2023 till 1 February 2025. Figure 1 shows the modelled surface mass balance (SMB) for the whole timeseries, starting in 1979. 2024 was not, regarding the SMB, an extreme year as 2022 was when precipitation, thus snowfall, peaked. Still, 2024 reenforces the upward SMB trend by being well above the average SMB. Snowdrift sublimation was also more than average in 2024, relating to the warmer than average conditions over Antarctica.

Furthermore, the operational simulation of RACMO (using version 2.3p2) for Greenland has been updated. These operational simulations are different realisations than those for the cloud research (experiment 4), primarily due to different data postprocessing needs and workflows. The operational simulations will be further extended, to include the 2025 NH summer and austral winter in the fall of 2025. This updated data set, as it belongs to published dataset, is shared on request. The public data repository at Zenodo will be updated later in 2025.

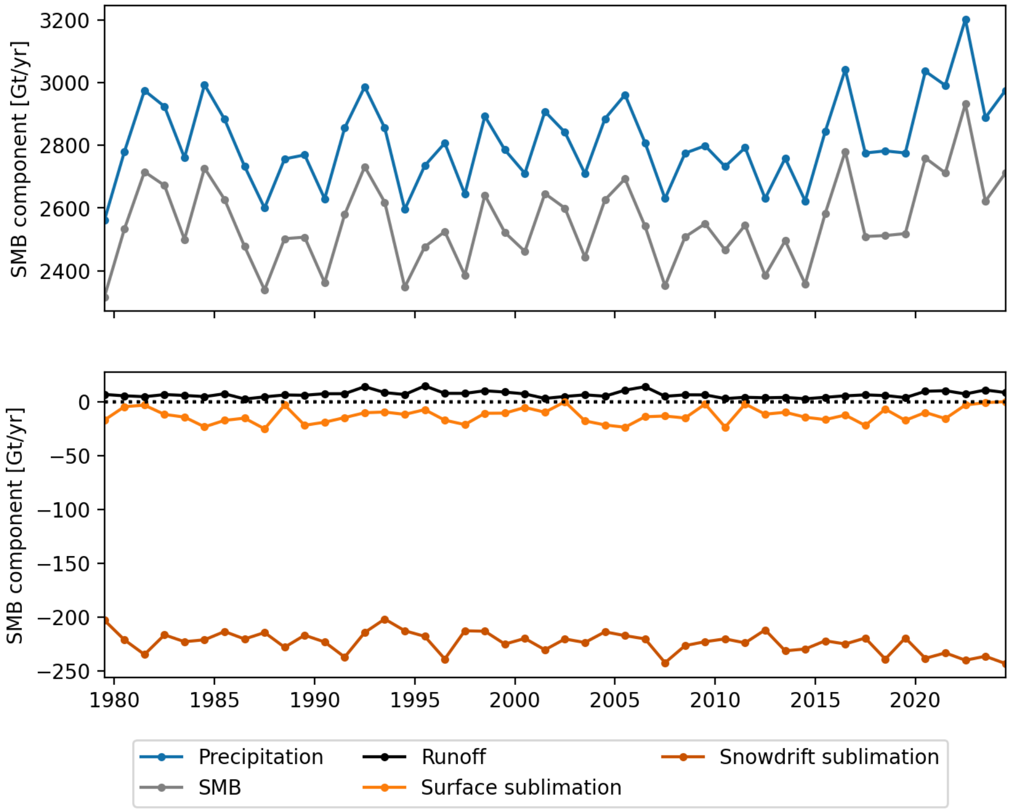

Figure 1: Modelled surface mass balance (SMB) and its components precipitation, runoff, surface sublimation and snowdrift simulation by RACMO2.4p1 driven by ERA5 for 1979 till 2024.

2. *Three long (1950-2300) transient simulations for the Antarctic climate and firn structure using RACMO2 and IMAU-FDM at 27 km resolution to study the potential for rapid transitions in firn demise.*

These simulations have not been carried out yet as we focussed first on the analysis of simulations carried out in 2024. The first results of these analyses are discussed briefly in the SPNLBERG final report for 2024.

3. *Run IMAU-FDM for the Greenland and Antarctic Ice Sheets with the new RACMO2 surface boundaries for the historical period as well as until 2100 with different climate scenarios.*

In the second half of 2024 and first half of 2025, we extended the timeseries of the FDM from 1957-2020 to 1939-2023 using ERA5-forced RACMO2p3.2 simulation and began testing on new model physics to include the effect of grain size on the density evolution. An accurate prognostic grain size evolution is need as grain size is controlling snow densification. The current operational version of IMAU-FDM uses a densification parameterization in which grain size is implicitly estimated, but the assumptions behind this parameterization are violated in a changing climate (Veldhuijsen et al., 2024). The planned new model physics employs a more physical description of densification which is grain size dependent. This model version, however, is still under development. Surface densification rates tend to be too low in the near surface compared to previous modeling and in-situ measurements because the overburden pressure at the surface is zero and small near the surface. We ran these comparisons for all locations for which we have firn cores. Figure 2 provide an example profile. Although this example exhibits most deviating firn densities below 5-meter depth, these deviations are mitigatable by a proper tuning of model parameters. A recurring challenge is the lack of densification in the upper meters of the firn core, where in reality densification, due to grain settling, is relatively fast, as correctly modelled by the current model version.

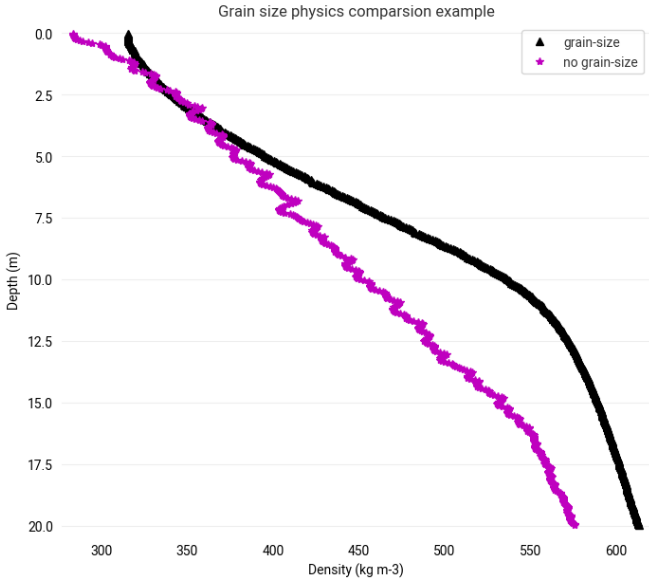

Figure 2: Example of the modelled firn densification by IMAU-FDM. The magenta line is derived with IMAU-FDM using the current densification parameterization, the black line with using a grain-size dependent densification formula.

Furthermore, sensitivity runs were performed using IMAU-FDM v1.2A (described in Veldhuijsen et al., 2023). These runs assess the model's sensitivity to input with different temporal resolution. So far, we found that simulations using daily input give up to 0.6-4.5 m more firn air content (FAC) compared to simulations using 3-hourly input for four selected ice shelves (Fig. 3). The mechanisms and feedbacks causing these differences are currently investigated over a larger scale, covering Greenland and parts of Antarctica.

Finally, we have updated IMAU-FDM so that it can be restarted from both after spin-up and after the end of the previous run. We are also working on model development, revamping the distributor, increasing model efficiency and memory use, creating unit and integrated testing for the model, and improving the output fields that are exported from a simulation.

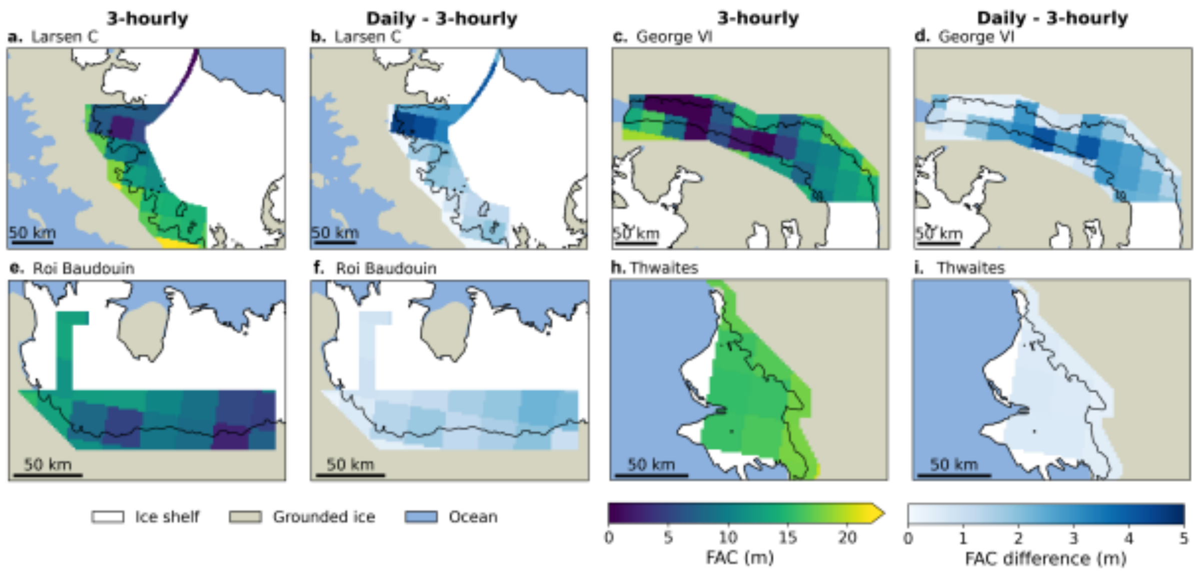

Figure 3: (a,c,e,h) Average FAC on the Larsen C, George VI, Roi Baudouin, and Thwaites ice shelves for the period 2000–2020, simulated with IMAU-FDM v1.2AD forced by 3-hourly RACMO2.3p2-ERA5 input. (b, d, f, i) Average FAC differences between IMAU-FDM v1.2AD simulations forced with daily averaged input and 3-hourly RACMO2.3p2-ERA5 input (daily minus 3-hourly).

4. *Dedicated reruns of RACMO2, forced with ERA5, to obtain high-temporal 3D atmospheric profiles, notably cloud characteristics, to be compared with EarthCARE, surface based remote sensed cloud data, and older remote sensing data.*

Continuing our work of 2024, described in the final report for 2024, we extended our evaluation of RACMO2.4p1 for the Greenland domain using the first observations of the EarthCARE satellite. Since EarthCARE was launched in May 2024, the retrieval algorithms are in active development. Resulting from this development, the first EarthCARE products were publicly released in January and March 2025. These involve level 1 backscatter and reflectivity observations, level 2 single-instrument derived cloud-, aerosol- and atmospheric properties and a target classification based on lidar and radar data combined. More products based on the combination of multiple instruments aboard EarthCARE are expected at the end of 2025. To be able to use these first months of available EarthCARE data, the RACMO2.4p1 Greenland (5.5 km) simulation has been extended until April 2025, where output was written for all timesteps that EarthCARE passes over the Greenland domain. Next to that, lidar and radar data based on the RACMO profiles were simulated to allow for a comparison with level 1 data. Our first comparison indicates that RACMO generally models clouds at similar locations as the EarthCARE observations show but seems to underestimate the extent and water content of both ice and liquid/mixed-phase clouds. An example for level 2 data is shown in Figure 3.

To investigate possibilities to improve cloud representation in RACMO, several sensitivity tests have been carried out regarding microphysical parameterizations. Several parameterizations used in the IFS are not tuned well for polar climates, especially when it comes to assumptions on number concentrations and aerosols that acts as nuclei for cloud formation or cloud phase changes. We tested the sensitivity of parameterizations for the Wegener-Bergeron-Findeisen process, the autoconversion to rain and the autoconversion to snow, by including more realistic aerosol and number concentrations for polar climates. We find that changing these parameterizations results in large changes in cloud content and cloud phase distribution and strongly impacts the radiation balance. This shows the potential of improving surface energy balance and surface mass balance estimates in RACMO by tuning cloud microphysical parameterization for the polar climate.

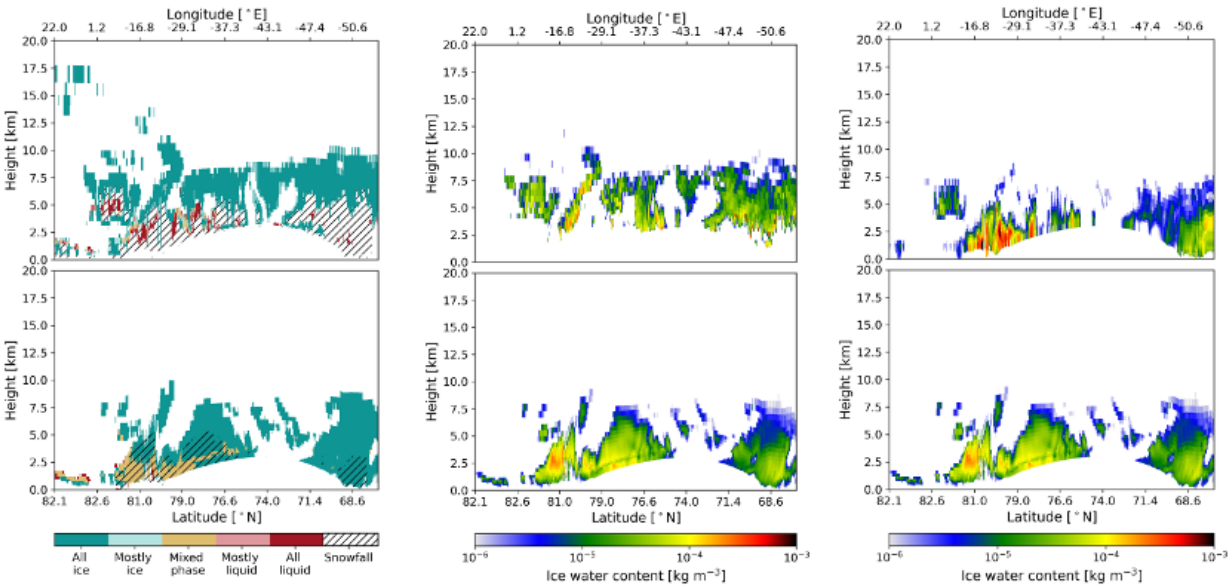

Figure 3: Comparison between RACMO2.4p1 (bottom row) and EarthCARE (top row) for a Greenland overpass on 04-02-2025. The left column shows the target classification based on lidar and radar data combined. The middle and right column show the ice water content from lidar and radar retrievals, respectively.

We will continue using the growing EarthCARE dataset to evaluate the current RACMO2.4p1, which involves regularly extending the Greenland 5.5 km simulation. We evaluate by both considering case studies and the overall statistical distributions of cloud representation in RACMO. Based on the EarthCARE observations, we will subsequently evaluate possibilities for parameterization tuning moving towards RACMO2.4p2.

In tandem with our evaluation of clouds over Greenland, an effort has been made to evaluate clouds over Antarctica as well. This evaluation was carried out as bachelor research project by David Bron. Here, we used a similar approach as for our Greenland evaluation, using co-located RACMO profiles to compare with EarthCARE observations for both level 1 and level 2 satellite products. This evaluation involved only the current RACMO2.4p1 version, without changing any microphysical assumptions. We focused on ten case studies, in the period between August 2024 and January 2025 and thus extended the Antarctic simulation (11 km) until January 2025. Considering the availability of EarthCARE products at the time of the analysis, we decided to focus on ice clouds specifically.

To evaluate RACMO using these ten cases, we compared the amount of grid cells containing cloud ice water within the frames for different altitude ranges (Fig. 4). For the lowest altitude range (0-2500m, Fig. 4a), the radar (CPR) is the most reliable instrument, since the lidar (ATL) often struggles here with attenuation. RACMO agrees relatively well with the radar observations for high ice cloud

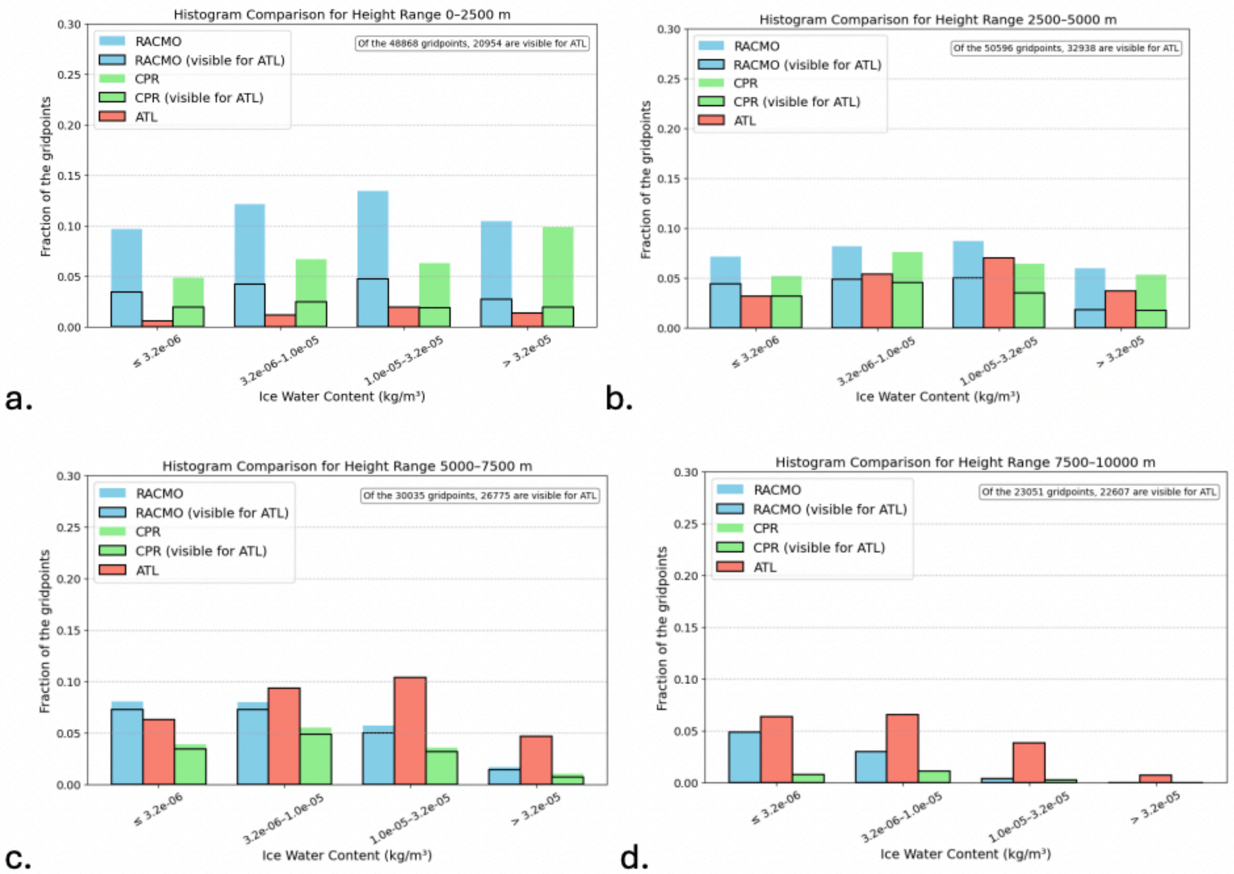

Figure 4: Comparison between RACMO2.4p1 and radar (CPR) and lidar (ATL) for ten selected cases. This figure shows the fractions of the grid points that are classified as ice cloud at different height levels. They are calculated by dividing the number of grid points within their cloud ice water content range in their respective height range by the total number of grid points in that height range, not including topography. The outlined bins at the front are the fraction of grid points that the lidar can observe before reaching full attenuation. On the top right corner, the figures show the total number of grid points in the height range and the total number of grid points in the height range that the lidar observes before reaching full attenuation

concentrations but overestimates the number of locations with low concentrations. In the range 2500-5000 (Fig. 4b), both the lidar and radar can give a useful estimate of ice cloud content, and RACMO agrees relatively well with both. At higher altitudes (Fig. 4c-d), the lidar gives the most reliable ice cloud retrieval. Here we see that RACMO underestimates the number of high clouds for almost all cloud ice water concentrations.

When more EarthCARE data is available, as well as level 2b cloud content data, which combines ATL, CPR and radiation measurements into one estimate, this analysis can be repeated with a larger number of EarthCARE overpasses and be extended to liquid clouds. To improve Antarctic cloud representation, microphysical sensitivity tests like those done for Greenland can be carried out for the Antarctic domain.

References

Veldhuijsen, S. B. M., van de Berg, W. J., Brils, M., Kuipers Munneke, P., & van den Broeke, M. R. (2023). Characteristics of the 1979–2020 Antarctic firn layer simulated with IMAU-FDM v1.2A. *The Cryosphere*, *17*(4), 1675-1696. https://doi.org/10.5194/tc-17-1675-2023

Veldhuijsen, S. B. M., van de Berg, W. J., Kuipers Munneke, P., & van den Broeke, M. R. (2024). Firn air content changes on Antarctic ice shelves under three future warming scenarios. *The Cryosphere*, *18*(4), 1983-1999. https://doi.org/10.5194/tc-18-1983-2024