

EMI R&D PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Modelling polar ice sheet climates at UU/IMAU
Computer Project Account:	spnlberg
Start Year - End Year :	2025 - 2025
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

The research of our group focusses on the understanding of the climate and surface mass balance of the Greenland and Antarctic ice sheets. The surface mass balance is the annual net sum of precipitation, sublimation, runoff and other smaller mass removing surface processes. Understanding and projections of the surface mass balance are, for example, of societal relevance as it directly relates to global mean sea level rise. For our research, we use the polar-adapted regional climate model RACMO, version 2.4p1 (van Dalum et al., 2024) and the firn densification model IMAU-FDM (Brils et al., 2022; Veldhuijsen et al., 2023).

In 2025, our research focussed on analysing and publishing the results from the simulation carried out in 2024 and further model development. As a result, less than expected simulations were carried out.

Summary of problems encountered

In 2025, we encountered few technical problems. The ECMWF sets a high standard with its up time of the HPCF, access and storage resources.

A point of attention, in our opinion, remains accessibility of ECFS data. In 2025, queueing of ECFS retrieving request was relatively limited. As a result, retrieving lots of data (~20 TB) from ECFS - using optimized scripts - was this year a manageable but remains multi-day exercise. If the queueing increases, e.g., the typical queue time to access a specific TAPE disk becomes more than 15 minutes, such large tape requests become extremely time consuming (again).

Experience with the EMI R&D Project framework

The application and reporting methodology is clear. Given the nature and size of our project the reporting and application procedure is always a bit of work, however, it is good that we justify in detail our requests and specify the outcomes of granted resources.

The decisions are communicated relatively late, which is not a problem if a request is granted. However, if a request would be rejected, there remains very little time to request resources on alternative (and less suitable) HPCF facilities, which is a sincere problem given that HPCF are critical for our research work.

Summary of results

We requested resources - 130 million SBU and 400 TB of storage - for 5 different sub-projects:

1. Extension of our operational RACMO simulations and model development.
2. Three ESG driven RACMO and IMAU-FDM simulations covering 1950-2300.
3. Renewal of the operational IMAU-FDM simulations for Greenland and Antarctica.
4. Evaluation of RACMO2.4p1 against EarthCARE observations.
5. Multidecadal HCLIM43 simulations covering the Antarctic Peninsula.

In 2025, our actual research projects deviated eventually considerably from the planned projects in the special project proposal, and only 42.8 million SBU of the requested resources have been used. Below we describe the results of the simulations carried out in 2025 and motivate the postponement or cancellation of planned projects.

1. Extension of our operational RACMO simulations and model development

As planned, in 2025 our operational RACMO simulations for Greenland (both the 2.4p1 and older 2.3p2 versions) and Antarctica (only the latest version 2.4p1) have been updated. As these simulations are short, the related HPCF costs are limited. The data of these simulations are made publicly available. An overview of available RACMO data is given at our website (<https://www.projects.science.uu.nl/iceclimate/models/racmo-data.php>).

Furthermore, we carried out a detailed evaluation of the drifting snow routing PIEKTUK-D used in RACMO2.4p1 for the Greenland Ice Sheet. Figure 1 displays the modelled blowing snow frequency and blowing snow transport. For this purpose, additional RACMO2.4p1 simulations covering 2012-08-01 until 2012-11-01 were performed to extract additional variables. This period was selected because it coincided with extensive profile and blowing snow observations at site S10 on the Greenland ice sheet (see insets in Figure 1 for the location of S10). These variables were needed to

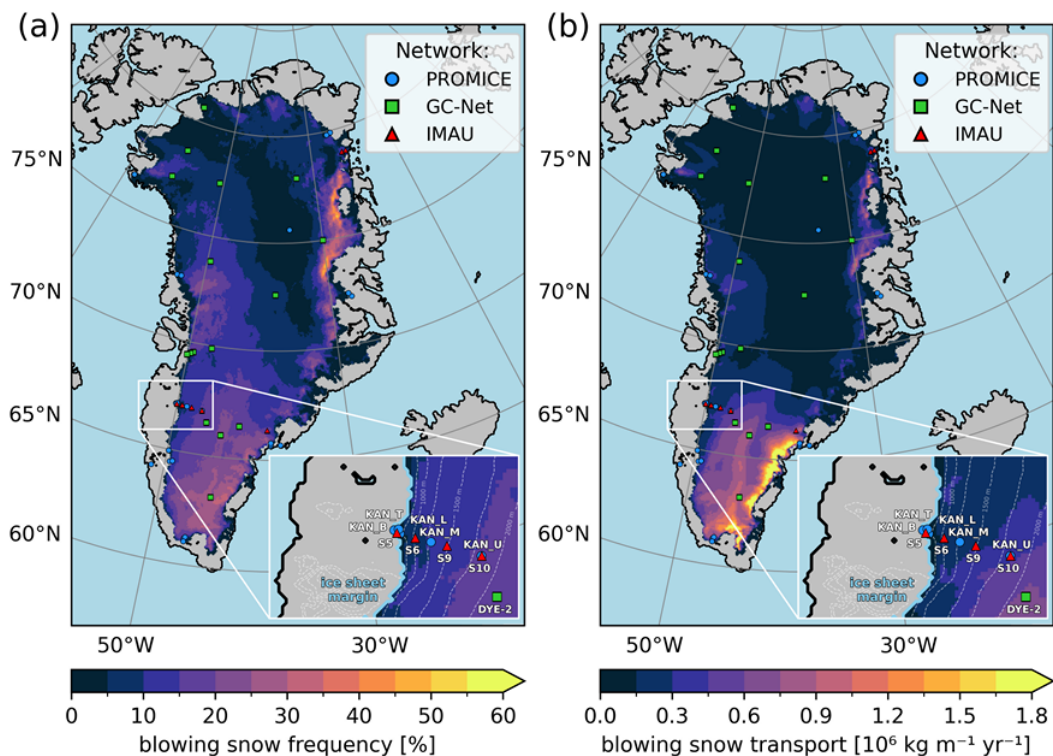


Figure 1: (a) blowing snow frequency and (b) total vertically integrated horizontal snow transport as simulated by RACMO2.4p1 during 2012 at 5.5 km horizontal resolution. The locations of the automatic weather stations on the ice sheet are also shown. Figure from Tax et al. (2026).

force the offline version of the blowing snow routine. The evaluation discovered and enabled us to fix some bugs in RACMO2.4p1. Next, sensitivity tests were done using the offline radiation model ECRad, forced with the RACMO2.4p1 vertical profiles. With these offline experiments, we investigated the effect of blowing snow on the radiation budget on the Greenland Ice Sheet. The results of this analysis were submitted to the journal *The Cryosphere* (Tax et al., 2026).

Lastly, the bugs that surfaced during the snow-drift research were corrected. To test the impact of these bug fixes, several short runs were carried out to test the influence of these bug fixes: a one-year simulation of the 5.5 km Greenland domain (year 2012); two one-year simulations of the 11 km Antarctic domain (year 2024); and a five-year simulation of the Antarctic Peninsula domain.

2. Three ESM driven RACMO and IMAU-FDM simulations covering 1950-2300

As mentioned in the special project proposal in 2025, these simulations were already planned for 2023 and 2025, also in 2025 these simulations were not carried out. The primary reason for the postponement in 2025 was a slightly different direction of the associated postdoc project. Instead of performing new simulations, we completed and submitted three papers based on simulations carried out in 2024 and earlier: Gilbert et al. (2026); Hofsteenge et al. (2026); (2025).

The first RACMO simulation of these planned simulations will be carried out in the second half of 2026, the final two RACMO simulations are planned for 2027, while it is expected that the related IMAU-FDM simulations will be done in 2028. All these simulations are now part of a separate PhD project, starting September 2026, which ensures these simulations eventually will be carried out.

3. Renewal of the operational IMAU-FDM simulations for Greenland and Antarctica

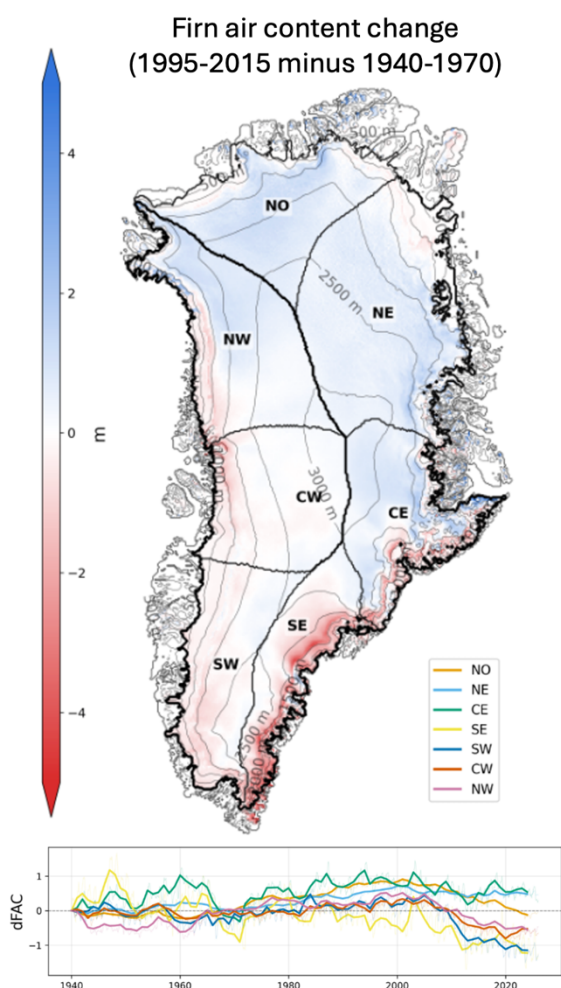


Figure 2: The upper figure shows the firn air content change over the Greenland Ice Sheet, simulated by IMAU-FDM. Displayed is the mean 1995-2025 firn air content minus mean over 1940-1970. The lower graph shows firn air content change per region, showing strongest losses since 2000 in the southern and western sections of the ice sheet. Thickening in the north and northeast has been persistent since the 1970, with declines in recent years.

During the second half of 2025, a landmark simulation of the firn layer over the Greenland Ice Sheet was run. For the first time, a reconstruction of the firn layer is now available since 1940, the new starting year of ERA5. It allows for an 85-year perspective on Greenland firn and its variability during this unprecedented long period. Since 1939, the Greenland firn layer has seen relatively large variability, with decadal thickening and thinning episodes that serve as a warning against overinterpretation of recent thinning trends. On the other hand, the loss of firn air content in recent decades remains unprecedented even over this longer period. Figure 2 shows an overall firn thinning rate in eastern, southern and western sections of the Greenland Ice Sheet. Thinning has been persistent since the 2000s, while a thickening trend was visible over much of the ice sheet between 1970 and 2000.

For the Antarctic Ice Sheet, such renewed simulation has not been made yet. Instead, we continued the sensitivity experiments for the Antarctic Peninsula Ice Sheet and the southern Greenland Ice Sheet to investigate how the climate forcing time step affects IMAU-FDM and the simulated firn layer under different climate regimes. Besides IMAU, several other research groups model the firn of ice sheets, using their own models but also a variety of climate forcing time steps, from hourly time steps to monthly time steps (Vandecrux et al., 2020).

To investigate the impact of this time step choice, we force IMAU-FDM with 3-hour, 6-hour, 1-day, and 1-month time steps at the surface. The modelled firn layer contains more pore space for larger forcing time steps, with highest sensitivities in regions with limited firn pore space due to seasonal melt (Fig. 3). On the APIS, the effect is strongest on the ice shelves, where firn air content increases by up to 15% for a 1-day forcing, and 44% for monthly forcing relative to the 3-hour forcing. In the southern Greenland Ice Sheet, the effect of the climate forcing time step is strongest for intermediate elevations, where a band with enhanced firn air content differences is apparent. The key in causing the differences in firn pore space is the representation of a diurnal cycle in the input data. A climate forcing time step greater than a day allows for a non-physical coexistence of snowmelt and sub-zero surface temperatures, leading to immediate shallow refreezing of meltwater. Subsequent melting removes refrozen ice rather than porous firn, reducing the amount of firn air that is lost through melting. We also found that firn density parameterizations can become unsuitable when applied outside the physical conditions or climate forcing time step on which they are based. These parameterizations lead to unrealistic firn densification and accumulation behaviour in the model. A manuscript based on these findings has been submitted to The Cryosphere (van den Aker et al., 2026).

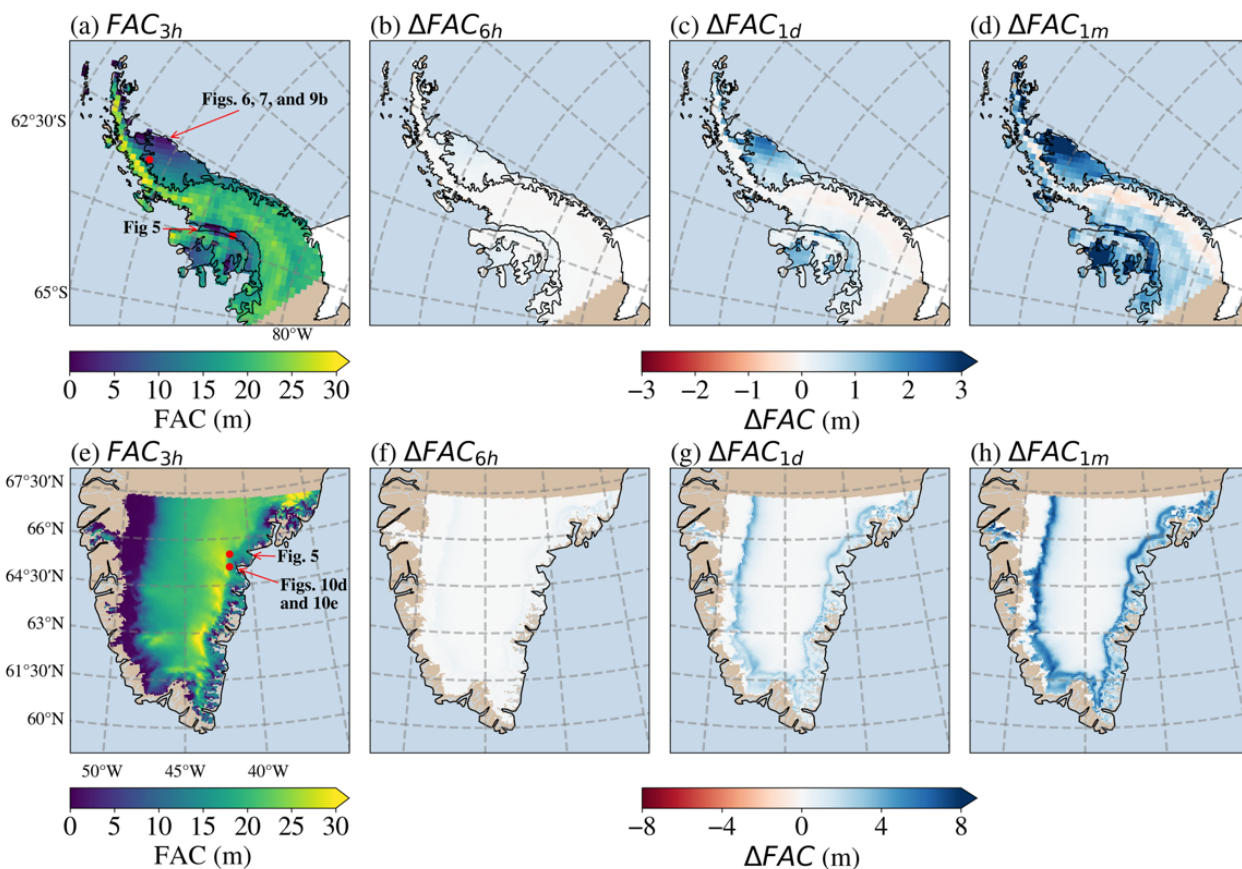


Figure 3: Maps of (a, e) the average FAC_{3h} and (b, d, f-h) ΔFAC , defined as the average FAC from simulations forced at coarser climate-forcing time steps minus the average FAC from the 3-hourly forced simulation. The averages are over the whole simulation period, i.e. 1979 - 2023 for the APIS and 1 September 1939 – 31 December 2023 for the southern Greenland Ice Sheet.

Lastly, the code of the IMAU-FDM firn densification model used for this run has a strongly modernized code base compared to previous runs. Code is now fully maintained on Git, model settings toggled and prescribed in toml-files, and an MPI-based job distributor is now used to distribute the run over available nodes. A small part of the SBUs for the project has been used to test the validity of the code compared to previous code versions.

4. Evaluation of RACMO2.4p1 against EarthCARE observations

Continuing the work carried out in 2024 and the first half of 2025, we extended the Greenland and Antarctica runs for the EarthCARE satellite period (Aug 2024 – ongoing). For these runs, we wrote additional output on all vertical levels for the time stamps of all EarthCARE overpasses. Additionally, we ran both domains without the modification of a few cloud parameterizations that were included in RACMO2.4p1 (van Dalum et al., 2024). While comparing these simulations with the retrieved cloud and precipitation observations from the EarthCARE satellite, we found that the model version without these modifications better matches the cloud observations. Therefore, we decided to use this as a starting point for further model development regarding clouds, precipitation, and radiation.

Additionally, we submitted a paper based on the work done earlier in 2025 (published as Feenstra et al., 2026). This paper demonstrates the potential of using EarthCARE observations for evaluating climate models by comparing RACMO model output with EarthCARE observations for two case studies. This work focused on both the Level 1 lidar backscatter and radar reflectivity products and the retrieved single-instrument cloud and precipitation products. The work done in late 2025 and in 2026 builds on this proof-of-concept paper by extending the EarthCARE-RACMO co-located timeseries and working towards evaluation over longer periods instead of case study-based. To this end, we developed methods to aggregate all EarthCARE overpasses and co-located RACMO model output during the EarthCARE period onto the RACMO grid. In this way, we can investigate biases in the spatial patterns of cloud and precipitation occurrence and water content.

5. Multidecadal HCLIM43 simulations covering the Antarctic Peninsula.

These planned HCLIM43 simulations have not been carried out, as the PostDoc leading this project, Kristiina Verro, left our research group early for a position at DMI, Denmark.

Instead, as part of a PhD project funded and started in 2025, we carried out a similar simulation using RACMO2.4p1. This simulation focussed on the contemporary climate and SMB (Figure 4a) of the Antarctic Peninsula. RACMO2.4p1 was run over the Antarctic Peninsula at 5.5 km grid resolution for the period 1979-2024, preceded by a spin-up simulation for 30-years to get a developed and stable firn layer.

The main objective of the project for which this simulation was carried out, is to simulate contemporary and future firn air depletion on the Larsen C ice shelf using IMAU-FDM, with input from this RACMO2.4p1 simulation. Surface melt is the most important output from RACMO2.4p1 that we need to model firn air depletion correctly. However, in RACMO2.4p1 the spatial distribution (Figure 4b) does not align well with satellite (Figure 4c) and surface (Figure 4d) observations.

We have, therefore, carried out an elaborate analysis on the causes of this difference in modelled and observed surface melt, relying on our in-situ observations of the surface energy balance. We have found that the discrepancy stems from three processes: 1) The energy supply for melting during Foehn wind events (dry, warm downslope winds) is not large enough, causing too little melt along the grounding line of the ice shelf. 2) There is too little cloud formation (Figure 5a), resulting in overall too much shortwave radiation and energy supplied in the northeast. 3) The melt-albedo feedback, which also depends on cloudiness, is too strong in RACMO2.4p1, which enhances the melt caused by too little clouds even more (compare Figure 5b with Figure 5c).

Following this analysis, we plan in 2026 to perform sensitivity tests on the 'refreezing grain size' parameter in RACMO2.4p1, which strongly influences the melt-albedo feedback. A weaker melt-albedo feedback might reduce the discrepancy between modelled and observed surface melt. Furthermore, the model causes leading to the observed cloud biases will be analysed in the ongoing EarthCARE cloud project (project #4). In addition, we have extended the Antarctic Peninsula simulation to include 2025 in the first half of 2026.

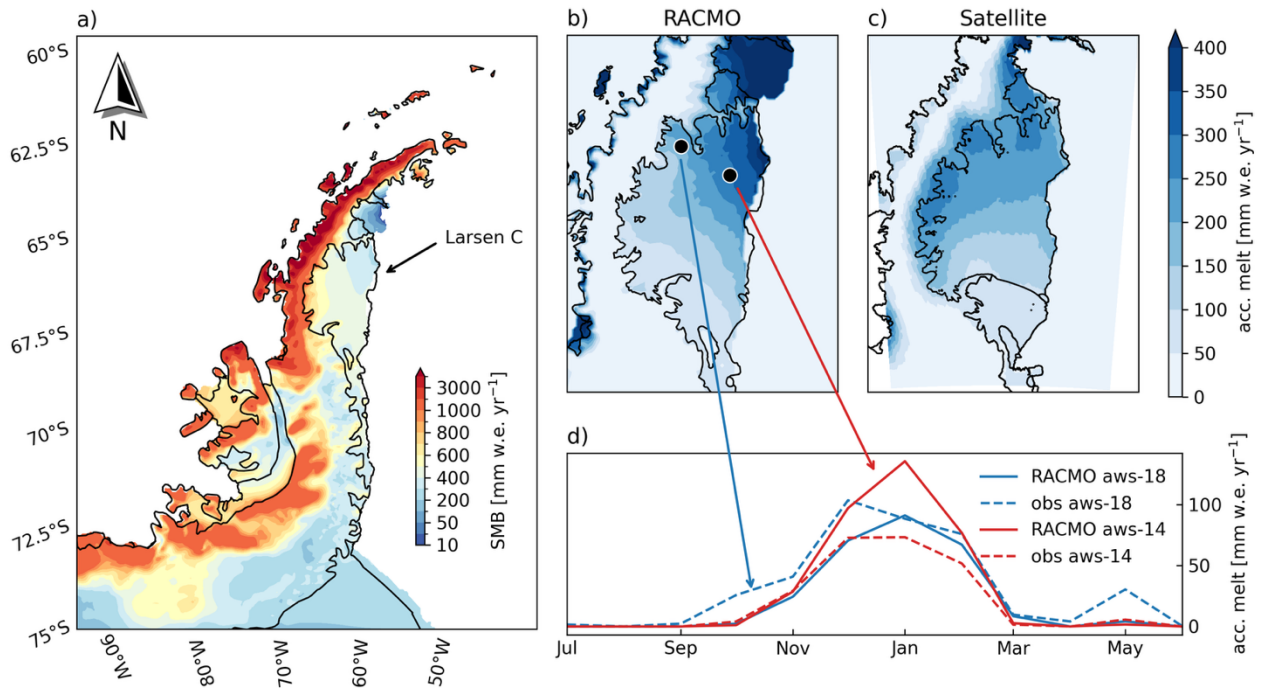


Figure 4: (a) Mean yearly surface mass balance between 1979-2024, modelled by RACMO2.4p1. (b) Mean yearly (accumulated) surface melt in the period 2011-2021, modelled by RACMO2.4p1. (c) As (b) but now for SSMIS satellite data from Di Biase et al. (2026). (d) Comparison of modelled and observed mean monthly (accumulated) surface melt between 2014 and 2022, at AWS-14 and AWS-18.

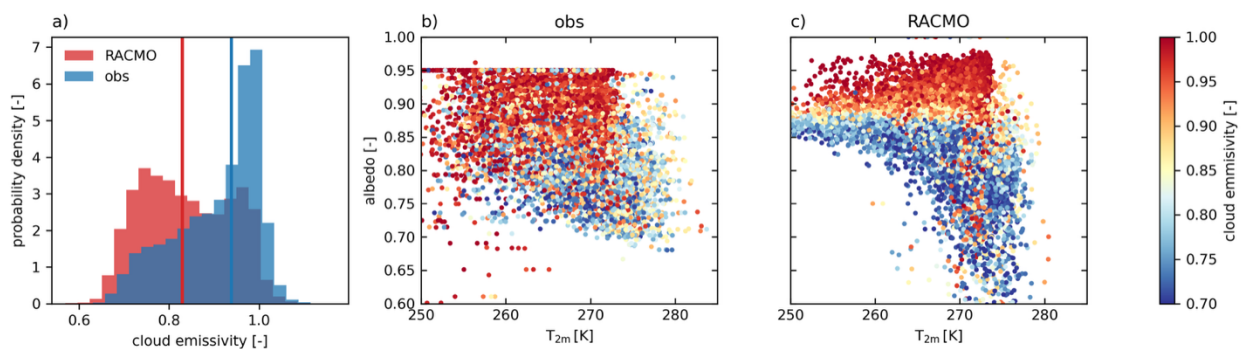


Figure 5: (a) Modelled and observed probability density of cloud emissivity - 1. is fully cloud covered, 0.7 is clear-sky - based on 2-metre air temperature and downwelling radiation. (b) Observed albedo as a function of the 2-metre air temperature, colour coded with the cloud emissivity. (c) As (b) but now modelled by RACMO2.4p1.

List of publications/reports from the project with complete references

We list publications based on RACMO and/or IMAU-FDM in which one of our group members, published in 2025 or 2026. These publications used the SPNLBERG budget of 2025 or of preceding years.

- Feenstra, T. N., van de Berg, W. J., van Zadelhoff, G. J., Donovan, D. P., van Dalum, C. T., & van den Broeke, M. R. (2026). Exploring new EarthCARE observations for evaluating Greenland clouds in the regional climate model RACMO2.4. *Atmos. Meas. Tech.*, 19(4), 1323-1344. <https://doi.org/10.5194/amt-19-1323-2026>
- Hofsteenge, M., Verro, K., Amory, C., van de Berg, W., Boberg, F., van den Broeke, M., Carney, M., Case, E., van Dalum, C., Fettweis, X., Hansen, N., Kittel, C., Mottram, R., van Tiggelen, M., & Hofsteenge, M. (2026). Historic and future surface mass balance contributions to Antarctic and Greenland freshwater fluxes from regional climate models. *ESS Open Archive*, 2026(0427). <https://doi.org/doi:10.22541/essoar.15002450/v1>
- Hofsteenge, M. G., van de Berg, W. J., van Dalum, C., Verro, K., van Tiggelen, M., & van den Broeke, M. (2025). On the non-linear response of Antarctic ice shelf surface melt to warming. *EGUsphere*, 2025, 1-26. <https://doi.org/10.5194/egusphere-2025-4176>
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- Veldhuijsen, S. B. M., van de Berg, W. J., Kuipers Munneke, P., Hansen, N., Boberg, F., Kittel, C., Amory, C., & van den Broeke, M. R. (2025). Emulating the expansion of Antarctic perennial firn aquifers in the 21st century. *The Cryosphere*, 19(10), 5157-5173. <https://doi.org/10.5194/tc-19-5157-2025>
- Verro, K., Äijälä, C., Pirazzini, R., Dacic, R., Maure, D., van de Berg, W. J., Traversa, G., van Dalum, C. T., Uotila, P., Fettweis, X., Di Mauro, B., & Johansson, M. (2025). How well do the regional atmospheric and oceanic models describe the Antarctic sea ice albedo? *The Cryosphere*, 19(10), 4409-4436. <https://doi.org/10.5194/tc-19-4409-2025>

As we actively share our data to the community and RACMO is one of the leading models in the field, about 40 to 50 papers per year are published in which either RACMO or IMAU-FDM data is used. We do not list those papers here.

Future plans

Our plans for the remainder of 2026 are described in the SPNLBERG progress report for 2026. Our plans for 2027 are listed in the SPNLBERG R&D project application for 2027.

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- Brils, M., Kuipers Munneke, P., van de Berg, W. J., & van den Broeke, M. (2022). Improved representation of the contemporary Greenland ice sheet firn layer by IMAU-FDM v1.2G. *Geosci. Model Dev.*, 15(18), 7121-7138. <https://doi.org/10.5194/gmd-15-7121-2022>
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