Regional Polar Climate Modelling

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Requested budget:

Year	HPCF (million SBU)	Storage (Tb)
2027	205	450
2028 & 2029	-	-

Outline

We request EMI R&D project time for our planned regional climate and firn (multi-year snow) simulations for Greenland and Antarctica. These simulations aim to improve the representation of polar processes in models, increase our understanding of ongoing changes and reduce uncertainties in projections of, for example, the contribution of ice sheets to global mean sea level rise. The proposed project is a continuation of the SPNLBERG special projects, funded since 2017.

Scientific relevance

The current and projected climate change in the polar regions will major impacts for local communities and the global climate system. In our research group, for which this proposal requests HPCF resources, we focus on the interaction of the atmosphere with ice sheets and peripheral ice caps and glaciers, aiming to increase our scientific understanding and improve ice sheet mass loss projections.

For the Greenland Ice Sheet, enhanced ablation at the lower ice sheet margins leads to continuous mass loss of the ice sheet, causing significant and accelerating global mean sea level rise (e.g., Otosaka et al., 2023; van den Broeke et al., 2016). Reliable mass loss estimates, however, require, for example, a precise description of the gradual spatial and temporal ice surface state change from pristine, high-albedo snow to algae-darkened glacial ice, as the surface albedo is the primary modulator of melt (e.g., van Dalum et al., 2020). Further inland, in the percolation zone, complex subsurface processes in the firn layer - the accumulating layer of snow that gradually compacts to ice - determine how much meltwater runs off into the ocean, and what part remains in the ice sheet (Noël et al., 2021). Melt and mass loss are, furthermore, strongly modulated by clouds and precipitation (Niwano et al., 2019). For example, an underestimated cloud cover leads to biases in downwelling longwave and shortwave radiation, and subsequently in the energy available for surface melt; locally overestimated precipitation also reduces local ablation through the delayed transition from bright snow to dark ice.

Similar processes are relevant for the Antarctic Ice Sheet. Possibly is the future ice sheet mass change positive, due to enhanced snowfall, but likely it is negative due to strongly enhanced ice discharge (Seroussi et al., 2023). In some regions of Antarctica, like the former Larsen B Ice Shelf, enhanced discharge is initiated by atmospheric processes that lead to ice shelf collapse (Glasser & Scambos, 2008). Hence, through this chain of processes, enhanced melt can lead to substantial global mean sea level rise.
It is therefore clear that predicting the future climate and surface mass balance - the net annual gain or loss of ice mass at the surface - of glaciers and ice sheets requires dedicated polar (regional) climate models. Our research group aims to understand, model and project these atmosphere-ice sheet interactions, leading to improved model descriptions of the relevant processes and reliable projections of future ice sheet mass loss. For this aim we use the polar version of the regional climate model RACMO and the firn densification model IMAU-FDM.

Model descriptions and justification

RACMO version 2.4p2

The regional atmospheric climate model RACMO, version 2.4p2, consists of the dynamical core of HIRLAM (Undén et al., 2002) and IFS physics cycle 47r1 (ECMWF, 2020), extended with detailed parameterizations of near and sub-surface processes over glaciated surfaces (van Dalum et al., 2024). Glaciated surfaces are represented with Lagrangian multilayer (30-70 layers) snow/ice profile to a depth of at least 30 m thick, connected to the atmosphere via a separate surface tile. Represented processes are heat diffusion, wavelength-dependent short-wave radiation penetration, snow densification and snow grain metamorphism, and water percolation, retention, refreezing and runoff. The albedo of the glaciated surface is derived using a grain-based narrowband albedo model (van Dalum et al., 2019). Lastly, snowdrift is represented by embedding the snowdrift model PIEKTUK-D (Déry & Yau, 2001; Gadde & van de Berg, 2024).
RACMO is, already for decades, one of the leading models in representing the climate and surface mass balance of the Greenland and Antarctic Ice Sheets. RACMO data is used in all leading mass balance studies like IMBIE (imbie.org, Otosaka et al., 2023), surface mass balance model intercomparisons (e.g., Fettweis et al., 2020; Mottram et al., 2021), and process studies (e.g., Glaude et al., 2024; Hofsteenge et al., 2025). Annually, 40 to 50 papers are published using RACMO data, demonstrating its wide use in the scientific community.
Besides the polar applications of RACMO as described here, RACMO has recently been used by the KNMI for Dutch and European climate projections (KNMI, 2023; Vautard et al., 2021) and is used for attribution studies of extreme events in Western Europe (e.g., KNMI, 2025). Our close collaboration with KNMI ensures that any model development carried out at Utrecht University will be beneficial for KNMI, and vice versa. Furthermore, as RACMO uses a rather recent IFS cycle, any major improvement in RACMO can be inspirational for improvements in the IFS code.

IMAU-FDM

IMAU-FDM is an offline single-column firn model, embedded in a script structure to run efficiently on single or multiple CPU nodes (Brils et al., 2022; Veldhuijsen et al., 2023). IMAU-FDM models the evolution of firn using a Lagrangian grid and includes the effects of heat diffusion, snow densification, and water percolation, retention, refreezing and runoff. IMAU-FDM improves the firn representation compared to RACMO in two ways. Firstly, in IMAU-FDM a firn column is brought to equilibrium prior a simulation. Trends and variability in the total firn air content and firn depth (i.e. snow surface elevation) as simulated by IMAU-FDM can hence be used to separated firn changes from ice sheet mass changes, whereas similar output from RACMO is affected by firn model drift. Secondly, IMAU-FDM allows for the use of numerous thin model layers throughout the whole firn column, whereas RACMO more readily aggregates layers for computational eficiency. This causes artificial multi-year height and firn air content trends, further invalidating RACMO output to study firn air trends.

We use IMAU-FDM to partition recent altimetry trends of the Antarctic and Greenland ice sheets into ice dynamical and firn depth changes (e.g., Pritchard et al., 2012; Schröder et al., 2019), to understand large scale water retention patterns in ice sheets (Brils et al., 2024; Veldhuijsen, van de Berg, Kuipers Munneke, Hansen, et al., 2024), and to project their future firn state (Veldhuijsen, van de Berg, Kuipers Munneke, & van den Broeke, 2024).

Proposed simulations

For 2027, we request budget for our planned RACMO and IMAU-FDM simulations to continue our scientific efforts to advance our understanding of the polar ice sheet mass balance and improve the representation of polar climate features in climate models. The proposed individual simulations are listed in Table 1 and will be discussed one by one below.

***Table 1**: Overview of planned model experiments.*

RACMO simulations		Budget	
Description - resolution - period		10^6 SBU	TB
RACMO2.4p2 updates	Antarctica - 11 km - 1979-2026	30	80
	Greenland - 5.5 km - 1945-2026	35	75
	Antarctic Peninsula - 5.5 km - 1979-2026	8	15
Long term Antarctic projections - ~25 km -1980-2300		60	40
RACMO2.4p2 Greenland projection - 11 km - 1980-2100		15	25
Greenland sea ice sensitivity - 11 km - 2x 1979-2026		10	15
Greenland with varying ice sheet geometry - 18 km - segments		10	20
RACMO budget		*168*	*270*
IMAU-FDM simulations			
IMAU-FDM updates	Antarctica - 11 km - 1979-2026	10	10
	Greenland - 5.5 km - 1950-2026	7	8
	Antarctic Peninsula - 5.5 km - 1979-2026	5	5
Greenland projection	Greenland - 11 km - 1950-2100	10	15
IMAU-FDM budget		*32*	*38*
Unforeseen and data rollover from 2026		*5*	*142*
Total requested budget		205	450

Updates of operational RACMO simulations

We serve the scientific community with RACMO-based estimates of the climate and surface mass balance of the Greenland and Antarctic ice sheets, which is the sum of precipitation, ablation and other surface mass fluxes. Early 2027, we will complete the development of RACMO version 2.4p2, which will have an improved description of cloud microphysics and precipitation processes, surface roughness, atmospheric aerosol concentrations, snowdrift, snow metamorphism and albedo decay compared to the current operational RACMO version 2.4p1. The improvements in the cloud scheme will have greatly benefited from evaluations with EarthCARE cloud and radiation observations. These observations allowed us, for example, to implement a temperature and hydrometeor density dependent parameterization of the fall speed of snow particles (see Figure 1), and to update static ice nucleating particle fields.

Subsequently, using this new model we plan to update our operational simulations of the climate and surface mass balance of the Greenland and Antarctic ice sheets in 2027. Furthermore, as part of an ongoing PhD thesis project, focussing on the stability of the Larsen C Ice Shelf, we will use version 2.4p2 for a dedicated high-resolution simulation of the Antarctic Peninsula. All these simulations are forced at the lateral boundaries and higher parts of the atmosphere by ERA5 fields - we anticipate that ERA6 will not yet be available. The simulation on the Greenlandic domain will start in 1945, when there are sufficient observations to constrain ERA5, while the Antarctic simulations will start in 1979. This later start date is required as prior to 1979, ERA5 exhibits a significant dry bias over East Antarctica, associated with the lack of observations (van Dalum et al., 2025).

The Antarctic and Greenland simulations will be run at resolutions of 0.1° (11 km) and 0.05° (5.5 km), respectively, which is currently, for these domains, the best trade-off between HPCF requirements and spatial detail. The Antarctic Peninsula run will be carried out on a resolution of 0.05° (5.5 km), which will resolve the complex topography

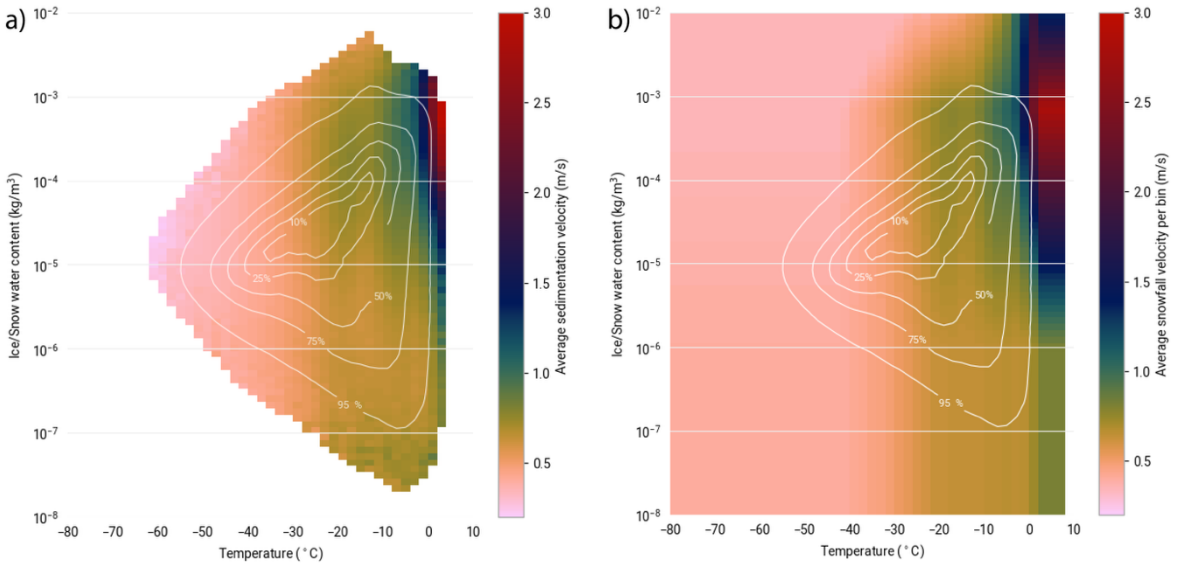

Figure 1: a) *Observed fall speed of snow particles as function of temperature (°C) and local snow and ice cloud content (kg/m^3), as observed by EarthCARE over Greenland and Antarctica.* ***b)*** *Parameterized snow particle fall speed as implemented in RACMO2.4p2. The observed particle fall speeds show a clear temperature dependence, related shape changes, and a weaker concentration dependence.*

of the Peninsula better than the whole-Antarctica run. Here, the resolution is bound by the hydrostatic nature of RACMO, with a finer resolution will probably lead to atmospheric artefacts (van de Berg et al., 2020). We will share the data with the scientific community and plan to write 3 publications based on these simulations.

Long term Antarctic projections with RACMO

As part of a dedicated PhD project starting in late 2026, and complementary to our planned simulations in 2026 and simulations proposed by our KNMI colleagues, we request budget for two long-term Antarctic simulations up to 2300. These two proposed simulations will be forced by CESM2 (CMIP7 version) and run for a CMIP7 low and high mitigation scenario. These simulations will complement our planned RACMO simulation in 2026, driven by IPSL with the SSP5-8.5 scenario (see SPNLBERG 2026 special project progress report). All these RACMO simulations will use a resolution of 0.2° (22 km), which limits the HPCF requirement to about 10 million SBU per modelled century.

These simulations will be used to investigate specifically the long-term fate of the Antarctic ice shelves. In a high-end emission scenario, melt and firn layer removal might expand far southwards over the ice shelves already during this century (e.g., Veldhuijsen, van de Berg, Kuipers Munneke, & van den Broeke, 2024), however, as the adjustment of the firn layer to climate takes decades or more, a similar southward expansion could occur with less climate change but on a longer term. As future Antarctic warming has uncertainties from both the future human greenhouse gas emissions and the modelled global response, it is essential to repeat these simulations using forcing data from different Earth System Models. A paper will be written analysing these simulations, and in a next phase of this project IMAU-FDM will be forced with the surface data to refine the representation of the firn evolution.

The EC-Earth driven high resolution RACMO simulations until 2300 KNMI is planning to run in parallel are primarily aimed to track atmospheric rivers. We will share our data for their project and vice versa.

21st century projection for Greenland with RACMO

Following on the upgrade to RACMO version 2.4p2, we propose a CESM2 driven simulation for the Greenland Ice Sheet to assess the impact of the improved cloud microphysics on the modelled projected climate and surface mass balance of the Greenland Ice Sheet. To limit the HPCF requirements, this simulation will be carried out on a resolution of 11 km. During the analysis, we will focus on the current and future impact of chances in cloud occurrence and cloud phase on melt and refreezing. For example, liquid water clouds both absorb more shortwave radiation and emit more longwave emissivity than ice water clouds with the same cloud water path and hence enhance melt more than pure ice clouds. A paper will be to present our findings to the scientific community.

Arctic sea ice surface forcing sensitivity for the Greenland Ice Sheet

The Greenland RACMO domain encompasses the Arctic Ocean north of Greenland, including the last ice area, where sea ice is prescribed as a lower boundary condition. The persistence of this multiyear sea ice refuge has become increasingly uncertain (Schweiger et al., 2021). Reduced sea ice in this region warms and moistens the lower atmosphere, altering the surface energy and moisture fluxes reaching the northern

Greenland Ice Sheet: previous coupled experiments show a winter surface mass balance increase from enhanced precipitation, but increased summer melt through enhanced sensible and latent heat fluxes and the melt-albedo feedback (Liu et al., 2016; Sellevold et al., 2022).

To quantify this atmosphere-cryosphere interaction within RACMO2.4p2, we propose two sensitivity experiments on the Greenland domain (11 km) covering 1979-2026, in which the prescribed sea ice boundary conditions are perturbed relative to a present-day control: (i) a reduced sea ice concentration in the last ice area, and (ii) an altered seasonal cycle of Arctic sea ice thickness. The 1979-2026 period spans the full observed Arctic sea ice decline (Stroeve & Notz, 2018) and matches the period of our operational simulations, allowing a robust evaluation of the seasonal and interannual surface mass balance response. These experiments provide a process basis for interpreting the longer projection runs, and to diagnose interactions between the Arctic last ice area and the Greenland Ice Sheet surface melt interactions.

Varying Greenland Ice Sheet topography RACMO simulations

In 2026, to support improving long-term (millennia) ice sheet simulations, we started a project to develop an emulator of the monthly precipitation fields as simulated by RACMO using monthly ERA5 or CESM2 output fields as predictors, using optimized U-Net machine learning techniques. We can now successfully emulate these monthly precipitation fields, both the mean state and their variability, both for the historical period and across different projections. A manuscript is in draft to describe this novel optimized U-Net emulator.

Here, we ask for HPCF budget for the next phase in this project, namely, to develop an emulator that predicts the modelled precipitation field by RACMO for (any) physically reasonable altered ice sheet geometry given monthly CESM2 data. We will commence with these simulations in 2026 and expand the database of geometries further in 2027. These simulations are run on a slightly reduced resolution (~16.5 km), which allows us to run 1000 model years, thus for example 40 times 25 different geometries, for 10 million SBU.

If we succeed in designing a topography-aware emulator, this would be a major step forward, as topography-following precipitation fields are the most uncertain forcing field for multi-century ice sheet simulations. Currently, the only method to have this precipitation-ice sheet interaction is by coupled Earth System Models, which require 4 orders of magnitude more HPCF resources than stand-alone ice sheet simulations.

Updates of operational IMAU-FDM simulations

In 2025 and 2026 several improvements in IMAU-FDM have been completed, leading to version 1.3. Besides numerous code and runtime optimalizations, IMAU-FDM now uses by default the dynamic densification model (Veldhuijsen, van de Berg, Kuipers Munneke, & van den Broeke, 2024), parameterised short-wave radiation penetration (required for the coupling of IMAU-FDM to RACMO2.4p2), and a novel reduced-complexity water percolation scheme.

With this new version, we will update our operational IMAU-FDM products for Greenland and Antarctica and run IMAU-FDM for the Antarctic Peninsula as part of a dedicated PhD project. These simulations will be forced at the surface with output of the RACMO2.4p2 simulations described above.

Compared to existing IMAU-FDM projections, we expect a more physically realistic response of densification to the recent gradual climate change, induced by using dynamic densification. Moreover, it is expected that the novel water percolation model solves the systematic runoff biases of RACMO and IMAU-FDM (e.g., Machguth et al., 2026) by introducing a more gradual transition from efficient melt water buffering in the higher percolation zone of ice sheets to limited melt water buffering in the ablation zone. Analysis of the Antarctic Peninsula simulation will particularly focus on how enhanced melt alters the firn state over ice shelves and how firn layer decay may induce ice shelf destabilization though hydrofracturing.

IMAU-FDM projection for the Greenland Ice Sheet till 2100

Next to the simulations with IMAU-FDM focussing on the recent past, we propose to carry out an IMAU-FDM projection for the Greenland Ice Sheet up to 2100. This projection is urgently needed, firstly because, unlike for Antarctica, such projections with IMAU-FDM have not yet been carried out and published. Secondly, the buffering capacity of the firn layer determines to a large extent the mass loss enhancement in a warming climate (Glaude et al., 2024; Noël et al., 2021). It is expected that the new IMAU-FDM version has a more realistic representation of this buffering capacity compared to preceding versions and hence will shed new light on the future Greenland Ice Sheet mass loss by surface melt and runoff.

Embedding

The proposed simulations will be carried out by our research team, consisting of 5 PhD students (one to be hired), 3 PostDocs and 4 staff members. This sufficient amount of manpower ensures that all simulations can be analysed and published timely, and the data is being shared, so that the HPCF resources will have maximum scientific impact. At the same time, the progress of these PhD and PostDoc projects depends on the proposed simulations here.

The proposed simulations build on past and existing special projects by our research group (see ecmwf.int/en/research/emi-rd-projects) and are carried out in close collaboration with the KNMI. Furthermore, the research is funded by and embedded in small and large national and European research projects, like EMBRACER (embracer.nl), OCEAN:ICE (ocean-ice.eu/), and FirnMelt (firnmelt.eu). Lastly, our research group is actively involved in the relevant scientific communities, like Polar CORDEX, IMBIE (imbie.org), ISMIP (ismip.org), and Antartica InSync (antarctica-insync.org).

Data sharing

All our data will be shared with the scientific community without constraints. On our data overview webpage (projects.science.uu.nl/iceclimate/models/racmo-data.php; for IMAU-FDM data a similar page is currently being prepared), all new simulations will be listed including where and how data can be obtained. Low temporal resolution data (e.g. monthly totals or averages) will be published on Zenodo (zenodo.org) or similar platforms. Due to the sheer size of high-temporal resolution data, these data cannot be published on public servers; these data will be available upon request.

Project impact

The proposed simulations by RACMO and IMAU-FDM are expected to advance our understanding of the surface climate processes on the Greenland and Antarctic Ice Sheets. The recently updated and state-of-the-art versions of RACMO and IMAU-FDM will increase our process understanding and reduce the uncertainties of the drivers of recent ice sheet mass loss. The new projections will help to narrow down the uncertainties in future mass loss of the Greenland and Antarctic ice sheets, particularly beyond the 21st century. Furthermore, as we will share all model data with the scientific community, we expect that the data generated with the requested resources will be used in numerous other projects, collaborations and scientific, peer-reviewed and open-access publications.

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