REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Netherlands

Principal Investigator[1]: Dr. Willem Jan van de Berg

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

Address: Princetonplein 5
3584 CC, Utrecht
The Netherlands
+31 30 253 3273

Other researchers: Dr. Peter Kuipers Munneke, Dr. Carleen Reijmer, Dr. Kristiina Verro, Dr. Valeria Di Biase, Dr. Maurice van Tiggelen, Dr. Linda van Garderen, Dr. Elizabeth Case, Sanne Veldhuijsen MSc, Thirza Feenstra MSc (IMAU/UU), Dr. Erik van Meijgaard (KNMI)

Project Title:

Modelling polar ice sheet climates at UU/IMAU

To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SPNLBERG**	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	130.000.000	-	-
Accumulated data storage (total archive volume)[2]	[GB]	400.000	-	-

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]	-	-	-
Total memory	[GB]	-	-	-
Storage	[GB]	-	-	-
Number of vGPUs[3]	[#]	-	-	-

Continue overleaf.

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3] The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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Extended abstract

Summary

In 2025, we plan to continue our successful research lines: improving research models and keeping operational model data sets up to date. Specifically, these models are the polar regional climate model (RCM) RACMO2, the high-resolution, non-hydrostatic RCM HCLIM43, and the firn densification model IMAU-FDM. We request budget for the following experiments, which are embedded in already funded PhD and PostDoc projects:

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.
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.
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.
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.
5. Multi-decadal HCLIM43 runs at 3 km resolution for the Antarctic Peninsula, to investigate the complex interaction between rugged topography, precipitation, surface albedo and snow melt.

These simulations aim to increase our understanding of the climate and mass balance of the Earth's two big ice sheets. Experiments #1 and #2 also serve the (cryospheric) scientific community, as these datasets are widely used to force e.g. ice sheet models or perform case studies of climatological extreme events. The data of these experiments will therefore be made publicly available on Zenodo. The results of experiment #3, will be subsequently used by ice sheet modellers to improve the understanding of ice shelf and ice sheet stability. Experiments #4 will be used to improve the representation of ice, liquid and mixed-phase clouds in RACMO, ideally leading to an updated operational model version. Finally, experiment #5 aims to improve our understanding of the very complicated climate-ice shelf surface interaction of the ice shelves of the Antarctic Peninsula. The requested HPCF budget and ECFS storage are summarized in Table 1.

Table 1: *Break-down of the requested resources.*

Experiment	**HPCF** (Million SBU)	**Data storage** (TB)
1) Operational RACMO2.4p1	2	50
2) Three 27 km RACMO2.4p1 simulations of Antarctica spanning 1950-2300	40	50
3) Rerun operational IMAU-FDM simulations and run new projections	20	25
4) Dedicated RACMO2.4p1 simulations for cloud modelling	20	40
5) Multi-decadal HCLIM simulations	40	20
Unforeseen (HPCF) and data storage rollover from 2024	13	215
Total	**135**	**400**

Overall motivation and aims

The years 2023 and 2024 proved again that the Earth's climate is warming and changing rapidly. Global surface temperatures persistently reached unprecedented values since at least the start of detailed observations in 1940 (Climate Change Institute, 2024). Antarctic sea ice cover reached record low values during the austral summer/spring of 22/23 and the following austral winter of 2023 (Norwegian Meteorological Institute, 2024). Combined with the declining sea ice in the Arctic and the rapidly warming Arctic, it is clear that climate change is strongly impacting the polar regions.

These polar changes have significant local impacts, e.g. the changing sea ice cover has great ecological consequences for both the Arctic and Antarctic. Apart from the local impacts, the warming climate leads to accelerated mass loss of the Greenland and Antarctic Ice Sheets (GrIS and AIS, respectively), resulting in an ever faster rise in global mean sea level. Higher atmospheric and oceanic temperatures over and around Greenland led to a continuous mass loss of the GrIS since ~1992 (Mouginot et al., 2019). The AIS has been losing mass since the start of observations in 1992 (Otosaka et al., 2023), primarily caused by ice dynamical losses of some larger outlet glaciers in West Antarctica.

Sea level projections are very uncertain (IPCC, 2021), primarily due to large uncertainties in the dynamic response of the GrIS and AIS and in their future surface mass loss in a warmer climate. Dynamic response projections of the AIS are uncertain due to our limited understanding and observations of the drivers of ice flow, and, subsequently, to which extent (rapid) self-amplification of mass loss through the Marine Ice Sheet Instability (e.g. Pattyn & Morlighem, 2020) is likely or even imminent. These future ice dynamical changes are strongly related to atmospheric processes, both indirectly through driving warm ocean currents and sea ice formation and drift, but also directly through surface processes. The break-up of the Larsen B and other ice shelves, following excessive surface melting, caused a rapid speed-up of its tributary glaciers (Scambos et al., 2004). Any new ice shelf break-up is likely to accelerate AIS mass loss, especially if that ice shelf is fed by one of the major outlet glaciers of West or East Antarctica. Especially for high-end warming scenarios, many Antarctic ice shelves will start to endure melt and become vulnerable to break-up (van Wessem et al., 2023). For Greenland, the uncertainty consists mostly of surface hydrological processes, affecting surface albedo, water storage, and runoff. Concluding, research on atmosphere-ice-sheet interactions is key to reduce uncertainties in the contribution of the GrIS and AIS to future sea level rise.

The Ice and Climate research group at IMAU, Utrecht University has been contributing to this polar atmospheric research field since 1990. Our primary numerical research tool is the polar adapted regional climate model RACMO, developed at the Royal Netherlands Meteorological Institute (KNMI). Since the first publication of a polar application (van Lipzig et al., 2002), RACMO proved to be an indispensable tool to estimate the climate and surface mass balance of the AIS (e.g., Lenaerts et al., 2012; van de Berg et al., 2006; van Wessem et al., 2018) and GrIS (e.g., Ettema et al., 2009; Noël et al., 2019; Noël et al., 2016), and provides data and knowledge that is used in numerous (high-impact) studies (e.g., Feron et al., 2021; Sutter et al., 2023; Tedstone & Machguth, 2022). Specifically, RACMO model output has been used in 'individual' ice sheet mass balance studies (e.g., Mouginot et al., 2019; Schröder et al., 2019; van den Broeke et al., 2016) as well as the community effort IMBIE (Ice sheet Mass Balance Intercomparison Excercise) to estimate and explain the mass change of the AIS and GrIS (Otosaka et al., 2023; Shepherd et al., 2018; Shepherd et al., 2020).

In parallel the model RACMO, our research group has been developing the firn densification model IMAU-FDM, to study the dynamics of the layer of compressed snow that covers the ice sheets, and started using HCLIM for high-resolution non-hydrostatic applications, such as the mountainous Antarctic Peninsula, where rapid changes are ongoing, but the highest possible resolution is required (order 1 km). IMAU-FDM firstly aims to provide accurate estimates of the evolution of the firn air content, as increases/decreases of the firn air content lead to firn depth increases/decreases as seen by altimetry satellites, which must be corrected for to convert volume changes to mass changes (e.g., Pritchard et al., 2012; Schröder et al., 2019). Secondly, detailed firn calculations allow to estimate more precisely the refreezing capacity of firn, which determines how much meltwater is retained and does not run off, which is as much as 45% on the GrIS and likely >99% on the AIS (Brils et al., 2024; Veldhuijsen et al., 2024). Furthermore, we started using HCLIM for simulations over rugged topography, for example in the Antarctic Peninsula. There, kilometre resolution, or less, is needed to resolve the interaction between topography and the large scale and local scale circulation such as föhn winds (Gilbert et al., 2022). RACMO, which has hydrostatic dynamics, is unable to resolve this interaction correctly (van de Berg et al., 2020).

Motivation and aims of proposed projects for 2025

In 2024, our research efforts focussed on 1) creating climate projections for the Arctic region and for Antarctic, using the new RACMO version 2.4p1; 2) improving and applying IMAU-FDM and emulators on high-resolution climate data and projections; and 3) improving the parameterizations in HCLIM to model the (Ant)arctic snow and sea-ice albedo better. In 2025, we plan to build on this research, but also take up the following new numerical research challenges.

1) Extended operational estimates of RACMO.

2 million SBU, 50 TB of ECFS storage

In 2023 and 2024, we have renewed our operational hindcasts of the climate and surface mass balance of the Greenland and Antarctic Ice Sheets, using RACMO version 2.4p1. The development of this new model version has been completed in 2023. In 2025 we will keep these operational hindcasts up to date by extending those simulations into 2025 with ERA5T boundaries. Upon request, we will also extend the Arctic simulation, which captures the new Arctic CORDEX domain, into 2025. All these simulations are relatively small efforts with a large scientific impact as they enable case studies of recent events. These simulations build on decades of model development and earlier long simulations, both facilitated by ECMWF grants from preceding years.

2) Three long (1980-2300) low resolution (27 km) Antarctic simulations with RACMO2.4p1.

40 million SBUs, 50 TB of ECFS storage

Rapid future warming, as expected for high-emission scenarios, will lead to a rapid demise of firn and refreezing capacity of many Antarctic ice shelves, with potentially catastrophic effects on ice shelf and ice sheet stability. Another scenario is a more gradual warming, with potentially a key role for mitigation by enhanced snowfall in a warmer climate.

To investigate these trade-off effects, we would like to carry out three RACMO simulations running until 2300, each following a different SSP scenario and with forcing kept constant after 2100 to give the firn layer time to equilibrate. These simulations will be driven by CESM2 boundaries, which will be generated in house. The lower model resolution (27 km) is chosen to limit computational costs, as similar runs on 11 km resolution would be 10 to 15 times more expensive. After completion and evaluation, data will be shared with ice modellers to improve centennial projections of ice shelf disintegration and mass loss from the AIS. We plan to run subsequentially IMAU-FDM with the RACMO surface boundaries, as described below.

These simulations had already been scheduled for 2023 and 2024 but have been postponed to 2025 for various reasons. In 2023, the delays in the development of RACMO2.4p1 forced us to postpone these simulations to 2024. In 2024, the delayed start of the high-resolution projection simulation for Antarctica and the Arctic consumed our budget, and we need the remainer of 2024 to analyse these projections. Nonetheless, these longer simulations are still very relevant to carry out for reasons outlined above.

3) Renewed IMAU-FDM simulations and projections for the ice sheets of Greenland and Antarctica

20 million SBUs, 25 TB of ECFS storage

Our operational IMAU-FDM simulations that estimate the historical evolution of the ice sheet firn layer, are still based an outdated IMAU-FDM version, and on output of the older RACMO version, 2.3p2. In 2025, we will renew all contemporary IMAU-FDM simulations, using RACMO2.4p1, in turn driven by ERA5. Furthermore, in 2024, for both Antarctica and the Arctic, we run RACMO2.4p1 to generate two projections until 2100 for the SSP3-7.0 scenario. In 2025, we use these simulations to drive IMAU-FDM and make additional projections of the future firn evolution. Lastly, we also force IMAU-FDM with the three long CESM2 driven RACMO simulations discussed above. These new IMAU-FDM simulations will also benefit from ongoing model developments (e.g. Veldhuijsen et al., 2024), and will provide training data for machine learning tools to estimate the firn evolution quickly from projections of other RCMs.

4) RACMO simulations for polar cloud evaluation and model development

20 million SBUs, 40 TB of ECFS storage

On May 29th, 2024, the ESA/JAXA satellite EarthCARE was launched. EarthCARE will measure cloud profiles in unprecedented precision and detail, and thus provides a unique opportunity to evaluate the modelled cloud state and the underlying parameterizations of microphysical processes. We will focus, in close collaboration with KNMI, on the representation of clouds over Greenland within the NWO funded project EarthCARE4Greenland. To expand the observational dataset, we also use ground based remote sensing data like those of the ICECAPS project (Shupe et al., 2013) and CloudSat/CALIPSO measurements postprocessed within the DARDAR project (Ceccaldi et al., 2013).

To be able to compare RACMO clouds in detail with derived cloud and backscattering profiles, dedicated re-runs are needed to ensure that the 3D atmospheric state is exported in insufficient temporal resolution for a one-to-one comparison between model and satellite. Furthermore, we plan first sensitivity simulations to inquire which parameterizations or tuning constants have most impact on the modelled cloud profiles and (surface) radiative balance. These experiments will lead to RACMO version 2.4p2.

5) Multi-decadal HCLIM simulations for the Antarctic Peninsula

40 million SBUs, 20 TB of ECFS storage

In 2023 and 2024, a considerable effort has been made to make HCLIM suitable for Southern Hemispheric domains and Antarctic conditions. For example, the modelled albedo of snow on sea ice was considerably too low, due to incorrect snow grain size estimates that were provided to the albedo model. The HCLIM snow grain size to density relation was updated using the output from the regional climate model RACMO version 2.3p3. This improved the albedo over sea ice. Next, we plan to improve the description of the albedo of snow in Antarctica, using SURFEX snow albedo scheme. In SURFEX, the snow grain size is a prognostic variable, allowing for more physically based albedo estimates. The SURFEX surface scheme is already embedded in HCLIM and active in our simulations to model the surface snow evolution, which simplifies the technical aspects. Initial tests in which the sea ice snow albedo modification was applied over land showed that a cold bias is introduced over Antarctica (Fig. 1), so we anticipate that a surface cold bias will develop over Antarctica when the SURFEX snow albedo will be used. This can be mitigated by adjustments in the parameterization of stable boundary and surface layers, e.g., improved representations of the surface roughness lengths of snow-covered surfaces.

After completion of these adjustments, a longer multi-decadal simulation will be carried out. This simulation, covering the Antarctic Peninsula with a horizontal resolution of 3 km, aims to provide a better description of the complex interaction to topography, atmospheric circulation and surface conditions. Especially the föhn events on the Larsen C Ice Shelf, located at the dryer, colder eastern side of the Antarctic Peninsula, are relatively poorly represented in hydrostatic models like RACMO. Non-hydrostatic models have shown to represent this better, but often lack a sophisticated representation of the snow layer covering Antarctica. This planned non-hydrostatic HCLIM simulation should combine the best of both worlds.

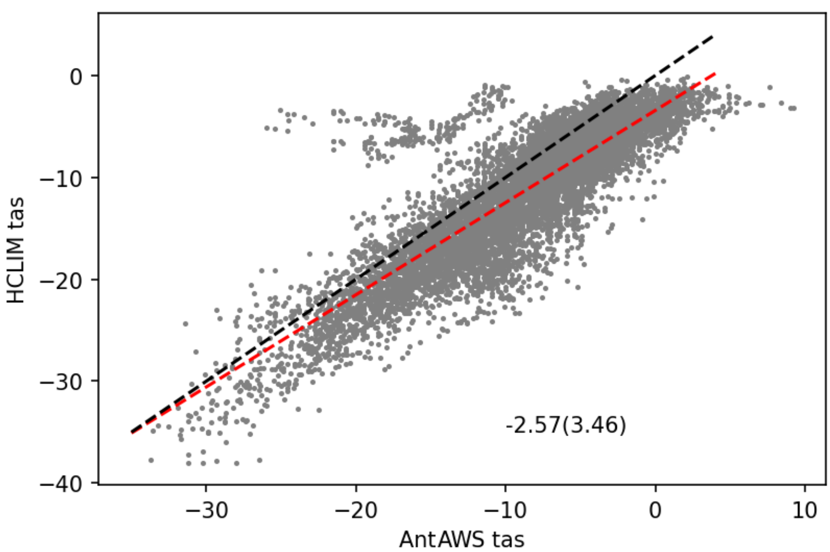

Figure 1: *Modelled versus observed near-surface temperature (tas) from the AntAWS dataset (Wang et al., 2023), for a HCLIM simulation covering the region of McMurdo Sound, Antarctica.*

General embedding of proposed research

The proposed experiments will be carried out and analysed by the polar atmospheric modelling research group of IMAU, Utrecht University. Two postdocs are responsible for running and analysing experiments #1 and #3, and #5, respectively, while two postdocs will be responsible for experiment #2. Experiment #4 will be carried out in a PhD project. Two more PhD projects in which RACMO data are used will start in 2025. Furthermore, two master and one bachelor student worked in the academic year of 2023/24 with either RACMO or IMAU-FDM data, and we expect this to happen as well in the coming academic year. Lastly, four senior staff members at UU and KNMI will oversee the experiments and subsequent analysis and reporting.

Description of proposed models

RACMO

The regional atmospheric climate model RACMO, version 2.4p1, is described in detail by van Dalum et al. (2024). It uses the hydrostatic dynamics of HIRLAM, ECMWF IFS physics, cycle Cy47r1, and it is extended with a detailed description of the atmosphere-surface interaction over glaciated surfaces and tuned for polar conditions. The RACMO code is fully parallel using MPI, has separate I/O and scales well on ATOS. For most of the simulations we run RACMO on 1024 cores.

RACMO is preferred above HCLIM in hydrostatic mode as the description of boundary layer and subsurface processes over glaciated surface, e.g., snow drift of the interaction of melt water interaction the snowpack, is currently superior in RACMO compared to HCLIM.

HCLIM

For our simulations with a resolution of 3 km over the Antarctic Peninsula, we use HCLIM43-AROME23, including the simple sea-ice model SICE. 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, several modifications have been implemented in the atmospheric surface and boundary layer schemes to better represent Antarctic conditions. The proposed research of this part of the project will be carried out in close collaboration with other HCLIM users at DMI, MetNo and KNMI, within the project PolarRES.

IMAU-FDM

IMAU-FDM is our 1-D firn densification model (Brils et al., 2022; Veldhuijsen et al., 2023). The simulations planned for 2025 will build on the modifications proposed by Veldhuijsen et al. (2024) and those proposed by Brils (2024), chapter 5.

Although RACMO also captures all physical processes modelled by IMAU-FDM, the latter has updated descriptions of surface snow properties, heat diffusion and compaction. Furthermore, it has a much higher vertical resolution (3 to 15 cm) throughout the whole firn column, as opposed to RACMO where deeper firn layers are much thicker. In IMAU-FDM the firn layer is captured in up to 1000 layers, while the snow model of RACMO employs 30 to 60 layers. Finally, IMAU-FDM is spun up to an equilibrium state using a reference climate, which could take over 1000 model years. As a result, the modelled evolution of the firn layer with IMAU-FDM does not suffer from long term model drift and artificial trend breaks.

Data

Monthly and yearly cumulated/average data of key variables of all simulation described here will be made publicly available on Zenodo after thorough evaluation and/or acceptance of scientific articles based on these simulations. For RACMO, these key variables are, for example, the components of the surface energy and mass balance, and near surface climate variables. (Sub)daily data will not be published on Zenodo, as it would require excessive storage space on this facility, but this data will always be rapidly shared on request without conditions, following UU/IMAU's open science policy.

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