REQUEST FOR A SPECIAL PROJECT 2024–2026

MEMBER STATE: Netherlands

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Project Title: Storylines of changing polar climates

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.	**SP** NLBERG	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2024	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2024**	**2025**	**2026**
High Performance Computing Facility	[SBU]	200.000.000	-	-
Accumulated data storage (total archive volume)[2]	[GB]	400.000	-	-

EWC resources required for project year:		**2024**	**2025**	**2026**
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

High-resolution climate models are essential for detailed projections of climate change in the Arctic and Antarctic. Building on existing work and embedded in European H2020 projects (PROTECT, PolarRES, and OCEAN:ICE) and in national research projects, our research group plans to use the regional climate models RACMO2.4 and HCLIM43, and the firn densification model IMAU-FDM, to carry out the following numerical experiments:

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 RACMO2.4 and IMAU-FDM.
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.
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.
5. 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.
6. Project the evolution of the Greenland ice sheet firn layer ice sheet until 2100 using IMAU-FDM.

These experiments will increase our knowledge of the polar climate for complementary storylines of the climate response given a certain emission scenario, both for this as coming centuries. They will also increase our knowledge of the complex interaction between topography, sea-ice, clouds, stable atmospheric boundary layers and precipitation. Lastly, the requested budget allows us to maintain our operational estimates of ice sheet surface mass balance up to date, which are of great value and intensively used within the cryospheric community.

Motivation and aims

In the last decade, anthropogenic warming and its far-reaching implications for the polar regions have become more and more apparent[1]. In the Arctic, sea ice extent is declining, the Greenland Ice Sheet is rapidly losing mass[2], the permafrost is thawing, and tundra wildfires are increasing[3]. Although natural decadal climate variability is larger over and around Antarctica, here also significant signs of anthropogenic warming become more and more apparent. Antarctica experienced a heat wave in 2022[4] and sea ice started declining in recent years[5], leading to unprecedent slow growth of sea ice in the 2023 austral fall[6]. Despite the Paris Agreement, greenhouse gas emissions are not declining, making the “middle of the road” shared socioeconomic pathway (SSP) SSP2-4.5 or even SSP3-7.0 the most likely pathways to 2100. Hence, more warming is to come, causing the polar climate and ice sheet mass balance to undergo more severe changes. Accurate dedicated projections of the Antarctic and Arctic climate and the response of the ice sheets to these and other climate scenarios (SSPs), are thus essential. Two criteria, however, need to be met.

Firstly, although reanalyses products like ERA5 and Earth System Model (ESM) intercomparison projects like CMIP6 provide estimates of the recent past and future polar climate, both lack the detail and specific polar process parameterizations for accurate assessment of, e.g., snow- and ice melt. Polar-adapted Regional Climate Models (RCMs) are the most suitable tool for accurate estimates of the past and future polar climate as they can run at high resolution and can employ dedicated parameterisations of polar-specific processes.

Secondly, every model has its own typical dynamical response to the projected warming, both ESMs and (polar) RCMs. A single or an ensemble realisation of one polar RCM forced by one ESM is very valuable, but fails to cover the wide range of possible outcomes for a given SSP. That is exactly the aim and value of the CMIP project. A similar broad exercise using RCMs, i.e., that each of the several available polar RCMs dynamically downscale realizations of dozens of ESMs, is infeasible. Therefore, within the EU Horizon 2020 project PolarRES, in which the

European polar RCM groups join forces, we employ the storylines approach[7]. For each of the two polar regions, we determine the two leading patterns of difference between the projected climate change by CMIP6 models. Figure 1, adopted from [8], shows the leading storylines for Antarctica, governed by changes during the austral summer. The leading and independent patterns are stirred by the amount of sea ice loss (SIE loss) and how much the breakdown of the stratospheric polar vortex (SPV) is delayed. Hence, selecting ESMs from an opposing storyline to be dynamically downscaled, while imposing that these selected ESMs can faithfully represent the Arctic or Antarctic climate, allows to capture the structural uncertainty within projections using only a few model simulations per RCM.

The proposed project hence firstly aims to improve the understanding and numerical representation of the current climate of the polar regions, and ice sheets in particular, by extending widely used high-resolution datasets (experiment 1) and sensitivity experiments (experiment 2). Secondly, it aims to contribute to a joint effort to assess the impact of the structural uncertainty in projections for the polar regions (experiments 3&4). Thirdly, it aims to provide the first high-resolution (27 km) long-term (until 2300) projections for Antarctica. Fourthly and lastly, it aims to provide detailed and physically derived estimates of the resilience of the firn layer over Greenland for different SSPs.

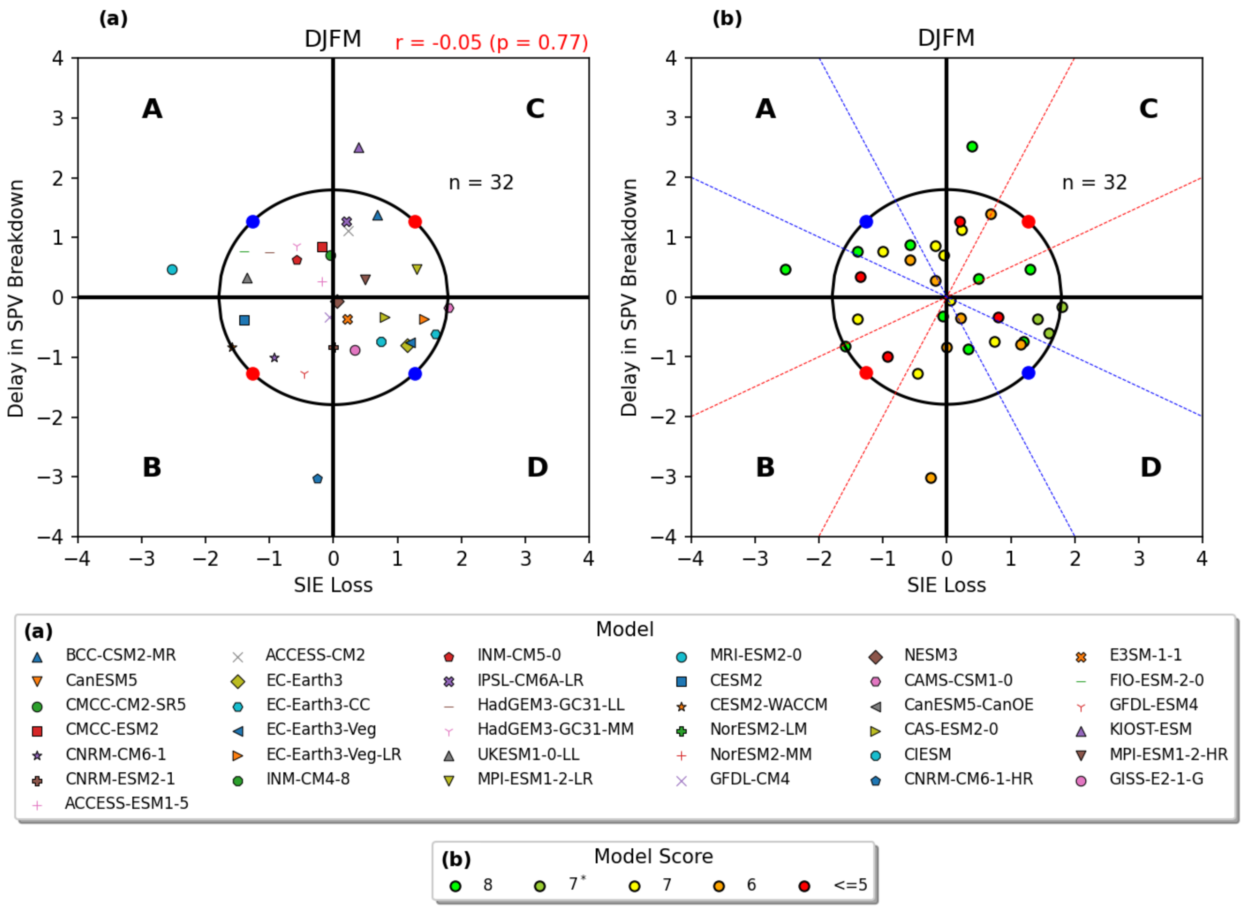

Figure 1: *Distribution of the normalized (scaled by global warming) and standardized model responses for SSP5-8.5 of each of the two leading drivers, sea-ice loss (SIE Loss) and delay in stratospheric polar vortex (SPV) breakdown, both during austral summer. Note that negative (positive) values of SIE loss anomaly correspond to more (less) absolute SIE loss than the multi-model mean. The ellipse encloses the parameter space within two standard deviations of deviations from the mean. The extreme (intermediate) storyline positions are shown as blue (red) dots located along ellipse. In* ***a)****, symbols used to represent models are provided in the legend. In* ***b)****, symbols show the ability of each CMIP6 to represent the present-day Antarctic climate is shown, ranging from excellent (8) to poor (5). Figure adopted from[8].*

Embedding and rationale of the proposed experiments

1) High-resolution simulation of the surface climate and mass balance of the Greenland and Antarctic ice sheets

Our research group has been developing and using the polar-adapted regional climate model RACMO for over two decades, with as main aim to accurately simulate the climate and surface mass balance (SMB, the net annual gain or loss of snow and ice at the surface) of the Greenland and Antarctic ice sheets. A short description of the latest and new version of RACMO, version 2.4, is given below. Combined with statistical downscaling of the SMB, we have created widely used (>400 unique users) data sets of the SMB and climate of these ice sheets, as well as for Svalbard, Iceland, the Canadian Arctic Archipelago, and the Patagonian ice fields[9-13]. RACMO data is currently used in typically more than 50 scientific studies per year. For example, these estimates are used in the IMBIE project[14], in which the cryospheric community provides the best possible estimates of contemporary mass loss of the Greenland and Antarctic ice sheets[2,15]; as well as studies to focussing on ocean-ice sheet interactions[e.g. 16,17].

The firn layer is the vertical transition zone from surface snow to glacial ice. It plays a crucial role in the mass balance of ice sheets, by buffering a significant fraction (~50% in Greenland and >99% in Antarctica) of the melt water. To compute this layer at a higher vertical resolution than what is computationally feasible in the snow model of RACMO, we have developed the firn densification model IMAU-FDM, which is described in more detail below. IMAU-FDM uses RACMO surface data as input forcing. Apart from process studies, IMAU-FDM data are widely used by other research groups, for example, to convert ice sheet volume changes into mass changes by combining it with radar altimetry data[18,19].

In 2024, we plan to extend these operational estimates from RACMO2.4 and IMAU-FDM. In contrast to a complete renewal of operational estimates, to be completed in 2023, the computational costs of these proposed simulations are relatively low (see Table 1). However, as the whole dataset needs to be stored on ECFS, the storage requirements are higher.

2) Sensitivity experiments with HCLIM

This experiment is also a continuation of research, initialised in 2022. HCLIM is the most suitable RCM to replace RACMO once centennial-long, kilometre resolution simulations are feasible for Antarctica and the Arctic. HCLIM is supported by an active, committed and well-defined community and benefits from developments in the operational NWP model HARMONIE. The proposed simulations will be carried out in close collaboration with national meteorological agencies KNMI, DMI and the Norwegian Meteorological Institute (MetNo) and will be used in model intercomparison studies on the interactions between sea-ice and clouds; between topography, föhn wind events and stable boundary layers; and lastly on sea-ice albedo. It is expected that each of the intercomparison studies will result in one or multiple publications.

These proposed simulations were initially planned for 2023. However, our research with HCLIM got delayed as adapting HCLIM to run for the Southern Hemisphere in general and, over Antarctica in particular, appeared to be more complicated than expected. Although HCLIM is currently technically functioning over Antarctica for different domains and dynamical cores, the quality of the results is not yet as expected from the performance of HCLIM for (polar) Northern Hemisphere simulations, suggesting that during the process to adapt HCLIM for the Southern Hemisphere errors have crept into the model code.

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

Experiment	**HPCF** (Million SBU)	**Data storage** (TB)
1) Operational RACMO2.4 and IMAU-FDM simulations	3	50
2) HCLIM experiments	20	15
3) First pair of RACMO2.4 projections for Antarctica and the Arctic	50	100
4) Second pair of RACMO2.4 projections for Antarctica and the Arctic	70	100
5) Three 27 km RACMO2.4 for Antarctica spanning 1950-2300	40	25
6) IMAU-FDM projections for Greenland	7	10
Unforeseen (HPCF) and data storage rollover from 2023	10	100
Total	**200**	**400**

3 & 4) High-resolution projections for both polar regions, using RACMO2.4

As motivated above, we propose to carry out two realizations of the Antarctic and Arctic climate each, using RACMO2.4, which is part of our promised contributions to the EU-funded project PolarRES. The first of these two realizations will be started in 2023, reducing the HPCF requirements for 2024. For both domains, the planned resolution of 11 km is a step forward compared to the existing projections. All simulations will start 1990, the historical period, and follow SSP3-7.0 for the period 2015-2100. This storyline is chosen as has significant and severe warming, more than SSP2-4.5, without using the greenhouse gas emissions and socioeconomic developments of SSP5-8.5, which are deemed unlikely in the light of current attempts to mitigate global warming. For the realisations, two ESMs will be chosen that represent opposing storylines (see above). For Antarctica, for example, these ESMs are most likely CESM2 and MPI-ESM1-2-LR, as these two ESMs belong to opposing storylines, perform well or excellent over Antarctica and have boundary conditions for RCMs for SSP3-7.0 readily available.

Along with our RACMO2.4 simulations, researchers at DMI (Denmark), MetNo (Norway), AWI Germany), University of Liège (Belgium), British Antarctic Survey (BAS, UK), and University of Helsinki (Finland) will carry out projections using their atmospheric, oceanic, or coupled regional models, on similar domains and with similar resolution, driven by the exact same ESMs. Analysis will focus on the differences and similarities between the modelled climate change patterns, and specifically on the role of clouds.

After completion of the simulations, a large selection of the data, following CORDEX guidelines, will be uploaded to ESGF nodes or a similar platform. Furthermore, a significant fraction of the raw data will be erased after completion of the data postprocessing, to reduce the long-term storage burden of these experiments.

5) Three long simulations for Antarctica

As part as our commitment to the EU-funded project OCEAN:ICE, we will carry out three simulations with RACMO2.4 on a resolution of 27 km. All these simulations will be driven by CESM2 boundaries. The aim of these experiments is to assess impact of fast or gradual warming on the melt, refreezing capacity, and meltwater runoff of Antarctic ice shelves. Our results will be combined with estimates of basal melt and iceberg discharge from Antarctic Ice Sheet, to be provided by other OCEAN:ICE teams, to estimate the total freshwater flux to the ocean These model data will subsequently be used to assess the long-term impact of Antarctic mass loss on the global ocean circulation.

6) Projections of the evolution of the firn layer of the Greenland Ice Sheet using IMAU-FDM

The last three decades exhibited warmer conditions than preceding decades and clearly showed the vulnerability of the Greenland Ice Sheet, as surface mass loss greatly increased[20], but it also demonstrated the importance of the firn layer. Without meltwater refreezing inside it, the mass loss would have been even larger[21]. Its capacity to buffer runoff is, however, reduced by the formation of ice slabs when melt increases[22]. These ice slabs inhibit deep percolation of meltwater, leading to an earlier onset of meltwater runoff.

Due to the limited vertical resolution in the firn model of RACMO, this effect of ice slabs is not well captured by RACMO. Therefore, we plan to model the projected evolution of the firn layer over Greenland Ice Sheet using IMAU-FDM. Similar simulations with IMAU-FDM have been carried out in 2022, however, these simulations have been discarded as severe numerical irregularities have been discovered in the output.

General embedding

The proposed experiments will be carried out and analysed by a large research group. Three postdocs will do the proposed RACMO and HCLIM experiments and subsequent data analysis. Another postdoc will carry the proposed IMAU-FDM experiments, while two PhD students will continue with analysing and publishing IMAU-FDM simulations carried out in 2022 and 2023. Furthermore, 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 2.4, uses the hydrostatic dynamics of HIRLAM and the ECMWF IFS physics, cycle Cy47r1. It is furthermore 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. Depending on the domain size, we use 256 to 1024 cores.
The development of RACMO version 2.4 has been completed in 2022, tuning is currently being finalized. More information can be found in the SPNLBERG progress report of 2023.

HCLIM

For our simulations with a resolution of 2 km over the Antarctic Peninsula, we use HCLIM43-AROME[23], including the sea-ice model SICE. HCLIM is the regional climate version of the numerical weather prediction model system ALADIN-HIRLAM, while HCLIM43-AROME is the convection permitting configuration of HCLIM. As described in the SPNLBERG reports of 2022 and 2023, HCLIM has been made suitable for simulations over the Southern Hemisphere and Antarctica.
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[24,25]. Although RACMO also captures all physical processes modelled by IMAU-FDM, the latter provides much improved estimates of the evolution of the firn layer than RACMO; IMAU-FDM 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.

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