REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE: The Netherlands

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Project Title: Bipolar regional climate projections

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.)	2023	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2023-2025: (To make changes to an existing project please submit an amended version of the original form.)		**2023**	**2024**	**2025**
High Performance Computing Facility	(SBU)	200.000.000		
Accumulated data storage (total archive volume)[2]	(GB)	400.000		

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.

Principal Investigator: Dr. Willem Jan van de Berg

Project Title: *Bipolar regional climate projections*

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, we request resources to carry out the following numerical experiments by our research group. We plan to use the regional climate models RACMO, version 2.4, and HCLIM43, and the firn densification model IMAU-FDM.

1. A CMIP6 model driven historical simulation and a projection till 2100 for both the Antarctic and Arctic at a resolution of 11 km, using RACMO.
2. Two pairs of two 30-year time slices (1980-2010 and 2070-2100) for both the Antarctic and Arctic, at 11 km resolution, using RACMO and driven by two other CMIP6 models. (8 simulations in total).
3. The first of three long (1950-2300) transient simulations for Antarctica using RACMO at 27 km resolution to study firn demise.
4. Estimate the evolution of the firn layers from 1) for Greenland ice sheet and 1) and 3) for the Antarctic ice sheet using IMAU-FDM.
5. HCLIM runs at 2 km resolution, to the Antarctic Peninsula and the adjacent western part of the Weddell Sea and test the sensitivity of the results to snow albedo, clouds, and aerosol settings.
6. Extending our operational estimates of the climate and surface mass balance of the Antarctic (11 km resolution) and Greenland (5.5 km resolution) ice sheets into 2023.

Firstly, these experiments will increase our knowledge of the polar climate for complementary storylines of the climate response given an emission scenario. Secondly, they will increase our knowledge of the complex interaction between topography, sea-ice, clouds, stable atmospheric boundary layers and precipitation and the representativeness of HCLIM for such challenging applications. 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 existing research

In the last decade, anthropogenic warming and its far-reaching implications for the polar regions has 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]. Though the changes may seem less apparent around Antarctica, nonetheless, the gradual ocean warming leads to decreasing sea ice cover[4,5], ocean acidification, the break-up of ice shelves – like the Conger ice shelf in spring 2022[6] - and mass loss of the Antarctic ice sheet[7]. Despite the Paris Agreement, greenhouse gas emissions are not declining yet[8], making the "middle of the road" scenarios SSP2-4.5 or even SSP3-7.0 the most likely pathways to 2100. Hence, more warming is to come, causing the polar climate to undergo more changes. Accurate dedicated projections of the Antarctic and Arctic climate and the response of the ice sheets to these and other SSPs, are thus essential.

Although reanalyses products like ERA5 and Earth System Model 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., melt. Polar adapted regional climate models 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.

Our research group has been developing and using the polar adapted regional climate model RACMO, with a specific focus on 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 description of RACMO is given below. Combined with statistical downscaling of the SMB, we have created widely used data sets (> 600 scientific publications) of the

SMB and climate of these ice sheets, as well as for Svalbard, Iceland, the Canadian Arctic Archipelago, and the Patagonian ice field[9-13]. These estimates are, for example, 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[2,7]; or studies to focussing on ocean-ice sheet interactions[e.g. 15,16].

We use RACMO to make estimates of the current climate and projections for the Antarctic and Greenland ice sheets. These projections give, for example, accurate estimates of the future mass loss of the Greenland Ice Sheet[17]. Here, we show a detailed example for Antarctica, where we estimated how much warming is needed to reach meltwater saturation of the firn layer during summers (Fig. 1)[18]. This meltwater saturation is a good first order estimate of ice shelf stability. Saturated firn allows for melt water ponding, and this "free" water can destabilize the ice shelf by hydrofracturing[19]. Meltwater saturated firn starts to occur once the snowmelt to accumulation (MOA) ratio exceeds 0.7. Using data from RACMO driven by ERA5, CESM2 simulations of the historical period (1950-2014) and the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, the 2 m temperature ($\boldsymbol{T_{2m}}$) is estimated for which temperature ($\boldsymbol{T_T}$) this MOA threshold of reached (Fig. 1a). Figure 1b shows how much warming ($\Delta\boldsymbol{T}$) is needed to reach this threshold $\boldsymbol{T_T}$ compared to the average climate of the past 40 years. This threshold is negative or close to zero for some parts of the ice shelves. There is an excellent agreement with those areas and observations from Sentinel-2 of melt ponds and their volume across Antarctica (not shown).

Finally, as the deeper part of the firn layer, the transition zone from surface snow to glacial ice, is not captured by the snow model in RACMO in sufficient detail, we estimate the evolution of the firn layer with the firn densification model IMAU-FDM, using RACMO surface data as input. Apart from process studies, IMAU-FDM data are widely used by other research groups, for example, to convert radar altimetry data over ice sheets, thus volume changes, into mass changes[20,21].

Rationale of proposed experiments

Despite the research we could complete with the support of ECMWF special projects in the past, numerous challenges remain.

Firstly, the operational RACMO version, RACMO2.3p2, uses IFS physics cycle Cy33r1, which has, for example, a relatively simple cloud microphysics scheme and no advection of hydrometeors. In 2022, we intend to use RACMO version 2.4, which uses IFS physics cycle Cy47r1. Besides many improvements in the radiation, turbulence,

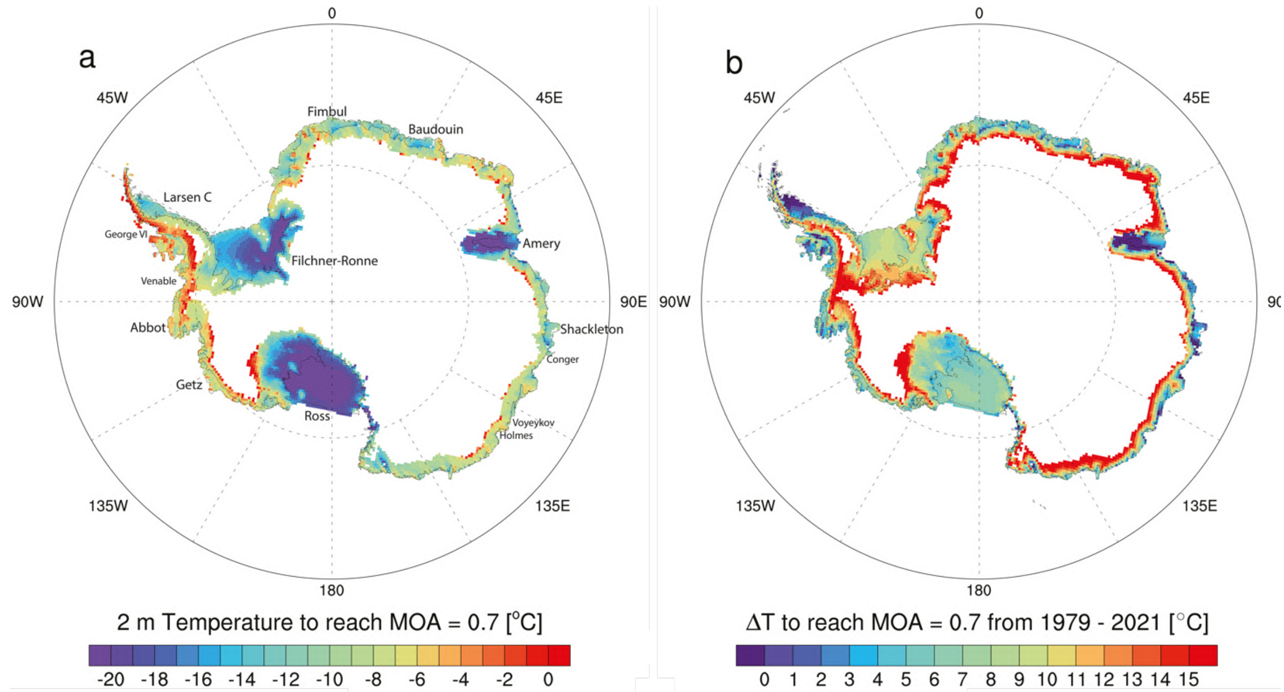

***Figure 1: a)** Intersect values of $\boldsymbol{T_{2m}}$ for which the MOA=0.7 threshold is reached ($\boldsymbol{T_T}$). **b)** The $\boldsymbol{T_{2m}}$ increase ($\Delta\boldsymbol{T}$) needed to reach the MOA=0.7 threshold with respect to the base climate (1979-2021) from RACMO2.3p2-ERA5. Values below zero $\Delta\boldsymbol{T}$<0 (dark purple) denote locations where $\boldsymbol{T_T}$ is already reached. **c)** Integrated 2015-2022 austral summer melt pond volume (m) from Sentinel 2.*

convection and surface schemes, this version has more detailed cloud microphysics by using six prognostic cloud variables. It has an explicit representation of cloud water and ice evolution and horizontal transport of hydrometeors. Both improvements are very relevant for our research, as the polar regions have a low abundance of aerosols and hence slower freezing of cloud water than elsewhere, which can now be explicitly tuned. Furthermore, due to the high resolution and the rugged terrain, the horizontal advection of falling snow will significantly impact on the modelled spatial snowfall patterns. With RACMO 2.3p2, the modelled spatial precipitation patterns do not fully agree with observations everywhere[22].

Secondly, projections have only been made using lateral boundaries from CESM2 and until 2100 due to computational constraints. These projections also cover only Greenland, Svalbard, and Iceland for the Arctic, and have a limited resolution (27 km) for Antarctica. It is, therefore, of great importance to complement these existing projections with projections using other CMIP6 models. Furthermore, the climate projections we propose for Antarctica will be run on 11 km resolution, providing much more detail over the Antarctic ice shelves, which are, as shown above, the most vulnerable Antarctic areas to climate change. The climate projections we propose for the Arctic which allows for an assessment of changes for the whole Arctic and a better comparison with similar projections carried out within the framework of Arctic CORDEX. We also plan transient Antarctic runs till 2300 using different SSPs at a lower resolution of 27 km to assess the decline of the firn pore space in Antarctica, leading to significant supraglacial runoff which may impact the coastal ocean circulation at the front of ice shelves. The first of these three simulations is planned for 2023, the other two for 2024.

Lastly, as RACMO's dynamical core is hydrostatic. Hence, its resolution is limited to about 5 km. The detailed topography-induced wind, temperature and precipitation patterns over the rugged Antarctic coastal zone or Greenland can only be resolved in full detail with simulations on kilometre scales. Therefore, we propose to continue our exploration of HCLIM in a non-hydrostatic set-up.

Proposed experiments for 2023

Given the motivation described above, we request resources for the following experiments.

1. For both the Arctic and Antarctic, a 1950-2100 realisation with RACMO2.4 at 11 km resolution, using a scenario and climate boundaries of a CMIP6 model yet to decide. Both domains will be compliant with the updated Arctic and Antarctic CORDEX domains, and similar to the domains used by the other project partners in PolarRES. We will choose the driving CMIP6 model and SSP (either SSP5-8.5 or SSP3-7.0) in consultation with our PolarRES partners. The estimated HPCF costs are 40 MSBU (million SBUs) and 50 TB of storage for each domain.
2. Complementary to these full simulations, we propose to run two pairs of two time slices (1980-2010 and 2070-2100) for both domains, driven by two other CMIP6 models as used for 1). This represents thus eight simulations in total, with a total HPCF cost of 70 MSBU and 80 TB of storage.
3. For Antarctica, the first of three CMIP6-forced long (1950-2300) projections at lower 27 km resolution to study firn demise and runoff in OCEAN:ICE. The estimated costs of this first run is 12 MSBU and 20 TB of storage.
4. Refine the estimate of the projected evolution of the firn layers from 1) and 3) of the Antarctic and Greenland ice sheets using IMAU-FDM. Due to the slow response of the firn layer, only continuous simulations are suitable as forcing for IMAU-FDM. Therefore, the simulation of 2) are unsuitable to be refined by IMAU-FDM. The estimated HPCF costs are 7 MSBU and 12 TB of storage
5. Carry out sensitivity experiments with HCLIM43 for the Antarctic Peninsula and the adjacent western part of the Weddell Sea on a resolution of 2 km. Various settings of the cloud, aerosol and snow albedo will be varied to assess the sensitivity of HCLIM, with a total simulation length of about 20 years. We budget 40 MSBU and 15 TB of storage for this aim.
6. Extending our operational estimates, driven by ERA5, of the climate and surface mass balance of the Antarctic and Greenland ice sheets into 2023. These simulations will be renewed in 2022 using RACMO2.4 and a resolution of 11 and 5.5 km, respectively. The SMB of the Greenland Ice Sheet will subsequently be downscaled statistically to 1 km resolution. As these simulations only cover one year, their costs are relatively low: 2 MSBU and 5 TB of storage, respectively.

Embedding and rationale

Experiments 1, 2 and 5 are part of UU's commitment to PolarRES, and experiment 3 to OCEAN:ICE. The aim of the projections, experiments 1 and 2, is to create a multi-RCM multi-CMIP6 model ensemble of high-resolution polar projections. This ensemble provides to assess the certain and uncertain aspects of polar climate change. Especially uncertainty exists, given a certain amount of global warming, on the induced changes in precipitation patterns, cloud cover and cloud type, surface melt of sea ice and low-laying part of ice sheets. One full simulation at 11 km resolution is proposed, to get a continuous and consistent evolution of the firn layer and ablation zone of the ice sheets and glaciers in the model domains. For Antarctica, we will also run until 2300 at lower resolution for firn and future runoff studies (experiment 3). The firn evolution of these simulations will be refined with IMAU-FDM (experiment 4). As two more full 11 km resolution RACMO simulations per hemisphere would be too demanding, two time slice pairs are proposed. These simulations give complementary insight into the atmospheric changes but are less accurate in projecting the response of ice sheets and glaciers to climate change. Output of all simulations will be uploaded to ESGF. It is expected that these simulations will be used in several publications.

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 a committed and well-defined community and benefits from developments in the NWP model HARMONIE. The proposed simulations in 5) will be carried out in close collaboration with KNMI, DMI and 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.

As discussed above, our operational estimates of the climate and SMB of the ice sheets of Antarctica and Greenland are the core data in many of the (high-profile) publications of our research group and are widely used in the scientific community. For example, since January 2021, 110 requests from international collaborators for the statistically downscaled products, including present-day and scenario projections for the Greenland ice sheet, the peripheral ice caps in Greenland, glaciers of the Canadian Arctic, Svalbard, and Iceland, have been handled. In addition, the native operational RACMO product for Greenland has been shared 60 times in the same period. For both ice sheets, RACMO data have been used in >600 publications.

The proposed experiments will be carried out and analysed by a large research group. Three postdocs and one PhD student will do the proposed RACMO and HCLIM experiments. One postdoc and two PhD students will do the proposed IMAU-FDM experiments. Furthermore, four senior staff members at UU and KNMI will oversee the experiments and subsequent analysis and reporting.

In brief, a large budget for 2023 is requested. However, this budget will support the research of several early-career scientists in our group, and our ECMWF-supported research has led to numerous (high-profile) publications. The requested budget will be well spent according to the aims of ECMWF special projects.

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 reasonably well if run on more cores. A doubling of the number of cores on which RACMO is run typically decreases the runtime by 45%.
RACMO version 2.4 is currently under development. It is expected to be ready for usage in the coming months. However, if unexpected severe delays occur during the tuning phase of RACMO2.4, we will revert to version 2.3p3[23] for the proposed RACMO simulations for 2023.

HCLIM

For our simulations with a resolution of 2 kilometre over the Antarctic Peninsula, we plan to use HCLIM43-ALARO, including the sea-ice model SICE. HCLIM is the regional climate version of the numerical weather prediction model system ALADIN-HIRLAM. HCLIM43-ALARO is the convection permitting configuration of HCLIM. HCLIM consortium member apply HCLIM over Europe, the Arctic and Greenland, and HCLIM is being step up over parts of Antarctica by MetNo.

IMAU-FDM

IMAU-FDM is our 1-D firn densification model[24]. Although RACMO also captures all physical processes modelled by IMAU-FDM models, IMAU-FDM provides much better estimates of the evolution of the whole 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. 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.

Total requested computational requirements

Experiment		HPCF (MSBU)		ECFS (TB)
1)	CMIP6 model driven historical simulation + projection till 2100 with RACMO	Arctic:	40	50
		Antarctica:	40	50
2)	Two times two 30-year time slices with different CMIP6 models with RACMO	Arctic:	35	40
		Antarctica:	35	40
3)	One 1950-2300 low-resolution simulation for Antarctica		12	20
4)	Firn densification work	Bipolar:	7	12
5)	HCLIM-SICE simulations for the Antarctic Peninsula		40	12
6)	Operational RACMO simulations (Greenland + Antarctica)		2	4
Unforeseen & unplanned (HPFC) and ECFS data rollover from 2022			4	172
Total			215	400

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