REQUEST FOR A SPECIAL PROJECT 2020–2022

MEMBER STATE: Netherlands

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Dr. Erik van Meijgaard (KNMI)

Project Title: Regional climate modelling of Greenland and Antarctica

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.)	2020	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2020-2022: (To make changes to an existing project please submit an amended version of the original form.)		**2020**	**2021**	**2022**
High Performance Computing Facility	(SBU)	20.000.000		
Accumulated data storage (total archive volume)[2]	(GB)	120.000		

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.

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Extended abstract

The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF as well as the Scientific Advisory Committee. The evaluation of the requests is based on the following criteria: Relevance to ECMWF's objectives, scientific and technical quality, disciplinary relevance, and justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests asking for 1,000,000 SBUs or more should be more detailed (3-5 pages). Large requests asking for 10,000,000 SBUs or more might receive a detailed review by members of the Scientific Advisory Committee.

Summary

In the last decades, the Antarctic and Greenland Ice Sheets are increasingly contributing to global mean sea level rise. Both enhanced ice discharge as increased ablation have been responsible for the mass loss of these ice sheets. The atmospheric forcing is directly related to ablation, but also indirectly to ice discharge as enhanced melting can destabilize buttressing ice shelves in Antarctica. Accurate estimates of ablation and snowmelt require dedicated high-resolution atmospheric models as several feedback processes enhance melt during the summer season. To provide these accurate estimates, we propose as our main research tool the polar adapted version of the regional atmospheric model RACMO2, version 2.3p2.

For the continuation of research projects, we request HPCF and ECFS storage for:

- Model development on the albedo of snow and ice, the key factor determining snowmelt onset and enhancement.
- Updating our operational estimates of the climate and surface mass balance of the Antarctic and Greenland ice sheets and their peripheral glaciers. These estimates are widely used by scientist all over the world.
- Performing projections of the future climate and surface mass balance of both ice sheets for a high-mitigation scenario. These projections will indicate whether mass loss of the ice sheets remains limited or that further mitigation measures might be needed.

Motivation

One of the major challenges of future climate change is to predict global mean sea level rise (GMSLR). For different reasons, the Antarctic and the Greenland Ice Sheets and their peripheral glaciers will significantly contribute to it (e.g. Church et al, 2013).

The Greenland Ice Sheet (GrIS), and peripheral glaciers and ice caps (GICs) are firstly losing mass due to atmospheric warming, leading to more ablation and subsequently a reduced or negative surface mass balance (SMB) (e.g. Noël et al, 2016; accepted). Secondly, ice discharge from marine terminating glaciers is enhanced due to atmospheric and oceanic warming (Mankoff et al, 2019). For the GrIS, enhanced ablation and ice discharge are responsible for 60 and 40% of the mass loss, respectively; for GICs the mass loss is primarily due to enhanced ablation (Van den Broeke et al, 2016).

The Antarctic Ice Sheet (AIS) is losing mass due to the dynamic interaction between ice flow and ocean-driven melt below the floating ice shelves that fringe the Antarctic coast (The IMBIE team, 2018). Nonetheless, atmospheric processes play an important role as warmer conditions on the ice shelves lead to an increase of melting over the ice shelves. Once that melt water can no longer refreeze, melt ponds may lead to fracturing and subsequent disintegration of the ice shelves, as has been observed for the Larsen A and B Ice shelves in the Antarctic Peninsula (Banwell et al, 2013). As ice shelves buttress the ice discharge from the AIS, disintegration of ice shelves will cause enhanced mass loss from the AIS and accelerated sea level rise (Fürst et al, 2016).

Even though snow and ice melt and subsequent ablation are clearly linked to temperature, the occurrence and magnitude of melt is largely determined by the albedo (shortwave reflectivity) and the efficiency of turbulent heat transfer in the typically stratified atmospheric boundary layer (Box et al, 2012). And once melt occurs, the capacity of the firn (multiyear snow) layer to refreeze or retain this meltwater determines whether meltwater can runoff or not (e.g. Noël et al, 2017). As both the albedo and firn processes include positive feedbacks, the SMB can vary from a local surface mass loss of 4 m per year to balance over a vertical elevation difference of only 500 meter, due to temperature differences, or tens of kilometres horizontally, due to spatial variations in precipitation. For accurate estimates of melt and SMB, high resolution (atmospheric) models, with detailed physical representation of the various processes in the snow and ice column that determine the surface albedo and meltwater buffering, are thus required. Although Earth System Models and reanalyses steadily improve in their spatial resolution and physical representation of glaciated surfaces, most accurate estimates of the contemporary and future climate and SMB of the AIS, GrIS and GICs are still derived with dedicated (i.e. polar adapted) regional atmospheric climate models (RCMs).

Concluding, understanding and projections of the current and future melt and SMB of the AIS, GrIS and GICs are essential for accurate projections of GMSLR, and for this task dedicated RCMs are required.

Research questions

In this proposal, HPCF and storage facilities are requested to enable the ongoing research projects at IMAU, Utrecht University, on the role of the atmosphere-glaciated surface interaction of the AIS, GrIS and GICs. This research has three major components: a) model development; b) accurate estimate of the contemporary climate and SMB of the ice sheets; and c) projections of the future ice sheet melt and SMB in a warmer climate. The research questions formulated here build on the output of projects carried out now or in previous years.

- a1) How does the spectral nature of both snow and ice albedo and the incoming shortwave radiation influence melt and ablation estimates?
- a2) How can, for glaciated surfaces, the representation of turbulent exchange during stratified but highly turbulent events be improved?
- a3) How much would the representation of the climate and precipitation patterns over rugged glaciated regions like Svalbard improve if a non-hydrostatic RCM is used?
- b) What was the climate and SMB of the AIS, Antarctic Peninsula and GrIS in 2018 and 2019?
- c) Are the changes in climate and SMB of the AIS and GrIS indeed limited if a high mitigation scenario (RCP2.6) is realized, compared to a 'business as usual' scenario (RCP8.5)?

Methods

The current generation of global climate models (GCMs) are improving on their representation of ice sheet surface – atmosphere interactions, but cannot yet be run on the resolutions needed to accurately resolve ice sheet margins or GICs. Therefore, we plan to use the Regional Atmospheric Climate Model RACMO2, statistical downscaling, the firn densification models FDM and SNOWPACK and start exploring the possibilities of the HCLIM model to simulate the SMB and climate of the AIS, GrIS and GICs.

RACMO2.3p2

RACMO2 is one of the leading RCMs in this research field and has been used for hundreds of studies of the SMB and climate of the AIS and GrIS and its peripheral glaciers, as well as other glaciated areas, e.g. the Canadian Arctic and Patagonia (e.g. Noël et al, 2017, accepted; Van Wessem et al, 2018; Lenaerts et al, 2013). RACMO2 is developed and maintained by the Royal Netherlands Meteorological Institute (KNMI) and consists of the dynamics of HIRLAM, version 5.0.6, and ECMWF IFS physics, currently version CY33R1. In order to represent the surface processes of glaciated areas, the polar version of RACMO2, hereafter simply referred to as RACMO2, is equipped with an interactive multi-layer snow model which includes firn densification, drifting snow processes, meltwater percolation, retention and refreezing and an albedo parameterization based on snow grain size evolution. In 2017, we improved the performance of RACMO2 by retuning snow albedo, snowdrift, firn densification and precipitation and cloud-precipitation conversion processes. Like HIRLAM, RACMO2 is a fully parallel model with separated I/O and along with RACMO2 model code comes a suite of batch pre- and postprocessing scripts. RACMO2 is typically run on 300 to 700 cores (SMT) at the supercomputing facilities of ECMWF.

Statistical downscaling

Even though RACMO2 is run typically at 5.5 km resolution, this resolution is not enough to resemble all spatial SMB patterns in the ablation zone. Therefore, for Arctic glaciers, ice caps and the GrIS the SMB is further statistically downscaled to a 1 km (Greenland) or 500 m (elsewhere) grid, which better resolves the smaller glaciers and ice caps in those regions. This downscaling procedure includes elevation and albedo corrections using as many as possible available SMB observations from the region of interest. As a result, the downscaled data provides superior estimates of the local and integrated SMB compared to the normal SMB estimates of RACMO2 (e.g. Noel et al, 2016). Statistical downscaling programs are run on single cores and require limited HPCF and ECFS resources.

Firn densification models

Although RACMO2 is equipped with a detailed physical firn model, the vertical resolution for buried snow and ice layers is limited due to computational and memory limitations. Therefore, the vertical firn profiles are refined using the firn densification models FDM and SNOWPACK, which use more vertical layers than the snow model in RACMO2 (Steger et al, 2017; Ligtenberg et al, 2018). By using these models, a more accurate estimate of melt water retention and refreezing is obtained. Moreover, by using two fundamentally different models, also an indication of model spread and uncertainty is acquired. Both firn densification models are run per model grid box as single core task.

HCLIM

We also intend to explore the use of HCLIM, the HARMONIE-AROME-climate model configuration in the ALADIN-HIRLAM NWP system. Unlike RACMO2, HCLIM can be run in non-hydrostatic mode, allowing simulations on kilometer scale resolutions. This constitutes a potentially significant improvement of modeled SMB as precipitation - a key parameter for the SMB - cannot be statistically downscaled in a robust way (Noël et al, 2016). HCLIM makes uses of the surface model SURFEX, which in its turn includes the advanced snow model Crocus, which potentially makes HCLIM very well suited for polar climate research.

Proposed experiments in order to answer the research questions

a1) In 2019, the implementation of the spectral snow and ice albedo model TARTES and the novel coupler SNOWBAL (van Dalum et al, 2018) is completed. It is expected that most of the simulations to investigate the impact on the modelled albedo, climate and SMB of the GrIS is completed in 2019 (see 2019 ECMWF progress report). For 2020, we request

   a) 1.8 MSBU and 9 TB of ECFS storage for 20 years of additional simulations for the GrIS

   b) 1.1 MSBU and 8 TB of ECFS storage to carry out a 1979-2019 ERA-Interim driven hindcast for Antarctica, in order to assess the impact of this model improvement on the resembled climate of Antarctica a2) It is expected that in 2020, only some pilot simulations will be carried out to inquire the impact of updated parameterizations of the turbulent exchange and the relevant surface properties. As these simulations are likely short, no particular HPCF and storage facility are requested.

a3) In collaboration with KNMI and DMI, we aim to explore the potential of using HCLIM by performing test simulations for Svalbard, regions of Greenland covering our observational sites, and/or the Antarctic Peninsula. Using existing hydrostatic and non-hydrostatic configurations of HCLIM, differences in the modelled atmospheric circulation and precipitation patters will be analysed and compared to existing simulations with RACMO2. However, as this project is also meant as research project for students of the UU master Climate Physics, it is uncertain whether this project will be carried out in 2020. If so, 1 MSBU and 4 TB if ECFS storage will typically be consumed, but these HPCF and ECFS needs are not included in the total request.

b) In 2020, we will update and extend our operational RACMO2 estimates of the climate and SMB of the AIS (27 km resolution), Antarctic Peninsula (AP, 5.5 km resolution) and GrIS and peripheral GICs (5.5 km resolution) to 2019. As these operational estimates are currently driven by ERA-Interim, we will redo the last 10 years of each simulation to verify that changing from ERA-Interim boundaries to ERA5 boundaries leads to only marginal changes in the RACMO2 output. Required facilities are 0.4, 1,3 and 3,4 MSBU and 3, 4 and 10 TB of ECFS storage for the AIS, AP and GrIS simulations, respectively. Subsequently, statistical downscaling will be applied on the output of the GrIS run and the simulations of FDM and SNOWPACK will be extended.

c) Complementary to the CESM2-driven 2020 to 2200 RACMO2 simulations for the AIS (27 km resolution) and GrIS (11 km resolution) for the business-as-usual scenario (RCP8.5), which are planned for the remainder of 2019, we plan to carry out two 2020 to 2100 CESM2-driven RACMO2 simulations for both the AIS and GrIS for the strong mitigation scenario RCP2.6. As the global climate more or less stabilizes around 2100 in the RCP2.6 scenarios, there is little incentive to extend these simulations beyond 2100. These experiments will explore whether limiting global climate warming to 1.5 - 2 K is sufficient to prevent dramatic increases of snowmelt (AIS) or ablation (GrIS). We choose for a single realization as we assess that the uncertainty induced by unknown internal climate variability is less than the uncertainty induced by reducing the spatial resolution of the run. The latter would be necessary if a small ensemble is run, otherwise HPCF costs are deemed too high. Required are 2.8 and 7.4 MSBU and 21 and 35 TB of data storage for the AIS and GrIS experiments, respectively.

Applications

- Even though RACMO2 is one of the leading RCMs in the field of polar meteorology, we are constantly developing the model in order to improve parts and parameterizations that show up as deviating when model output is evaluated against observations. Our model development has three aims: improving our understanding of the driving processes of mass losses and gains of glaciated surfaces, improving estimates and projections of the climate and surface mass losses and gains of glaciated surfaces, and providing routines and best practices for other model developing groups.
- To specify the last point, the (to be) developed parameterizations are primarily relevant for other RCM and GCM groups with a focus on polar research. For example, using a state-of-the-art albedo model introduces also the need of a snow grain evolution model, as the snow grain size primarily determines the albedo of clean snow. As a result, our albedo method is not suitable for numerical weather forecast models; the computational burden is too large in comparison to the gain in forecast accuracy. For climate models our albedo model is favourable. Firstly, the computational burden is not as critical as for numerical weather prediction models. Secondly, on seasonal time scales preventing “drift” of the modelled albedo becomes increasingly important. Our narrowband albedo approach is therefore primarily useful for (surface) models like SURFEX, HCLIM or CESM2, which already include a rather detailed physical description of glaciated areas.
- After completion of the simulations, we will decide whether the migration from ERA-Interim to ERA5 as driving reanalysis for our RACMO2.3p2 simulations would allow (a) dedicated publication(s). With or without dedicated publication, these updated operational estimates will be made publicly available. Our operational estimates of the climate and SMB of the AIS and GrIS are used by

numerous scientists, leading to ~600 scientific publications, reports and presentations on GrIS and AIS climate and mass balance (based on a search in Google Scholar using "RACMO **and** Greenland **or** Antarctica"). Our model results have been used in past IPCC reports and will be used in the upcoming SROCC and AR6 synthesis reports.

The model data are not downloadable from a server but all data are freely available on request. We adopted this approach as it provides no significant hurdle for other researchers to obtain the data, but it encourages interaction between our data users, so that the chances are reduced that model data is interpreted erroneously. Moreover, we can always be sure our collaborators get the latest and best data.

- The simulations of the climate and SMB of AIS and GrIS for a strong mitigation scenario will be used to analyse whether limiting global warming to 1.5 - 2 K is indeed sufficient to largely reduce the contributions of these ice sheets to global mean sea level rise. We currently cannot exclude that even for this limited amount of warming, the GrIS will enter a phase of slow but steady and irreversible mass loss. For the AIS, in particular the enhancement of melt over the ice shelves is relevant. If this melt enhancement is limited, the likely future disintegration of ice shelves for a high emission scenario is avoided, which reduces the chance of rapid mass loss through unbounded ice discharge. We are aware that the results will not be included in the upcoming IPCC AR6 assessment report as the cut-off deadline for paper submission is the end of 2019.

Embedding

The proposed model runs will be of vital importance for several on-going and fully funded PhD and Postdoc projects at IMAU, Utrecht University. These PhDs and Postdocs will carry out the majority of the model simulations and the subsequent data analysis. The PI will manage the computing resources and will provide local support for running RACMO2. Erik van Meijgaard at KNMI will provide additional model support for RACMO2 and HCLIM.

Total computational requirements

Research question			HPCF demand (MSBU)	ECFS demand (TB)
Ta1)	Narrowband albedo	GrIS:	1.8	9
		AIS:	1.1	8
a2)	Turbulent exchange		0	0
a3)	HCLIM exploration		0	0
b)	Partial rerun and extension operational climate and SMB products	AIS:	0.4	3
		AP:	1.3	4
		GrIS:	3.4	10
c)	2020-2010 RCP2.6 projections	GrIS:	7.4	35
		AIS:	2.8	21
Unforeseen (HPFC) and ECFS data rollover from current projects			1.8	30
Total			20.0	120

In total, the proposed runs require an estimated 20 MSBU of high-performance computing facilities. As we archive model output in detail, the data storage request is significant with 90 TB plus 30 TB rollover from 2019. This storage is needed to allow detailed analysis of the model output at a later stage of the research.

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