# REQUEST FOR A SPECIAL PROJECT 2019–2021

**MEMBER STATE:** The Netherlands

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Bert van Ulft and Erik van Meijgaard (KNMI, The Netherlands)

**Project Title:**

Present-day and future climate of Antarctica and Greenland modelled with RACMO2 and HCLIM.

| | | |
|---|---|---|
| If this is a continuation of an existing project, please state the computer project account assigned previously. | **SPNLBERG** | |
| Starting year:<br>(A project can have a duration of up to 3 years, agreed at the beginning of the project.) | 2019 | |
| Would you accept support for 1 year only, if necessary? | YES ☒ | NO ☐ |

| **Computer resources required for 2019-2021:**<br>(To make changes to an existing project please submit an amended version of the original form.) | | **2019** | **2020** | **2021** |
|---|---|---|---|---|
| High Performance Computing Facility | (SBU) | 23.000.000 | | |
| Accumulated data storage (total archive volume)[2] | (GB) | 92.000 | | |

*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] 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. W. J. van de Berg, Utrecht University

**Project Title:** Present-day and future climate of Antarctica, Greenland and the Russian Arctic modelled with RACMO2 and HCLIM.

# 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 and Technical Advisory Committees. 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 will receive a detailed review by members of the Scientific Advisory Committee.*

## Summary

For all low-lying coastal zones across the globe, ongoing and future global mean sea level rise (GMSLR) constitutes a considerable threat. The largest future contributions to GMSLR are projected to be caused by mass losses from the Antarctic and Greenland Ice Sheets and other glaciated regions such as the Russian and Canadian Arctic, Svalbard and Patagonia. For the Greenland Ice Sheet (GrIS) and most smaller glaciers and ice caps, atmospheric warming directly causes mass loss through enhanced surface melt and runoff, negatively impacting the surface mass balance (SMB). For the Antarctic Ice Sheet (AIS), enhanced melt is expected to saturate the firn layer in the coastal areas, which will destabilize ice shelves at some point, removing their buttressing effect and increasing ice discharge. All these processes will further accelerate GMSLR. Accurate projections as well as a thorough understanding of the physical processes at the ice-atmosphere interface in these regions are thus essential for future coastal security.

In the projects proposed here, we use the latest polar version of the regional atmospheric climate model RACMO2, a leading model in this field, to explicitly calculate the contemporary and future SMB of multiple glaciated regions at high spatial resolutions. Projects include the future SMB and snowmelt on the Antarctic Peninsula; the first SMB estimate of the three glaciated archipelagos in the Russian Arctic and implementation and testing of a novel spectral albedo model within RACMO2, with the potential of greatly improved albedo and hence SMB estimates. Finally, we aim to explore the possibilities of using the model HCLIM for future SMB research.

The proposed runs will build on completed and scheduled simulations for 2018.

## Motivation

Mass losses from glaciers, ice caps (GIC) and the ice sheets of Antarctica and Greenland (AIS and GrIS) are the main drivers of ongoing global sea level rise (GMSLR) (Church et al, 2013; Bamber et al., 2018). The AIS and GrIS are the two largest fresh water bodies on Earth and store a water volume equivalent to 56 and 7.3 m of GMSLR, respectively, and not long ago these ice sheets were thought to lose only a significant fraction of their mass on time scales of millennia. In contrast, GIC represent a potential GMSLR equivalent of about 0.4 meter, but in accordance with expectations rapidly respond to climate change on time scales of well below a century. Hence, in the 20$^{th}$ century GIC are believed to have dominated the contribution of land ice to GMSLR with about 0.6 mm yr$^{-1}$ to GSMLR. The primary drivers for this mass loss ware post-little ice age and early anthropogenic warming, respectively. Since 2000, however, the GrIS and AIS contributions to GMSLR have rapidly increased, with mass losses for each now are in the range of 0.5 to 1 mm GMSLR yr$^{-1}$, due to substantial atmospheric and ocean warming (Van den Broeke et al, 2016; The IMBIE team, 2018).

For the 21$^{st}$ century and beyond, even larger contributions are projected (e.g. Van Angelen et al, 2013; DeConto and Pollard, 2016), however with great uncertainty. In fact, the unknown contributions of the GrIS and AIS dominate the uncertainty in projections of future GMSLR. For low lying coastal zones and deltas like The Netherlands, future GMSLR poses a large threat, so accurate global and regional sea level rise projections are essential.

For GIC and the GrIS, enhanced snow and ice melt and subsequent runoff are the primary causes for the recent increases in mass loss (e.g., Van den Broeke et al, 2016; Noël et al, 2018). However, insufficient in-situ data are available to assess the magnitude of these fluxes based on observations alone, while no remote sensing techniques exist yet to separate the contributions if individual processes to mass loss. That is why regional climate models play a pivotal role in assessing the magnitude and causes of SMB decline. In these models, snow and ice melt and subsequent meltwater runoff can only be modelled accurately if sufficient resolution and detailed physical descriptions of albedo (reflectively) and melt water processes in firn (multiyear snow) are used. For example, the albedo of snow and ice, which controls the energy available for melt, is varies strongly as function of wavelength and snow properties (e.g. Gardner and Sharp, 2010). Fresh and clean fine-grained snow has an albedo approaching one for visible wavelengths, but for the near- and far infrared, fresh snow albedo is mostly less than 0.2. Snow metamorphism due to aging or melt moves this transition from high albedo to low albedo to shorter wavelengths. As a result, the broadband albedo of snow decreases from 0.85 for fresh snow to about 0.7 for old snow, doubling absorption of shortwave radiation and greatly enhancing melt water production. Glacier ice, which surfaces once all snow has melted away, has an even lower albedo of 0.3 to 0.5, depending on the impurity content. This powerful positive melt-albedo feedback - melt reduces albedo, which further enhances melt - underlines the necessity to model snow and ice albedo correctly, as relatively small errors in modelled albedo will and cumulate into large deviations by erroneous evolution of the snow/firn pack through the summer. Concluding, snowmelt and ablation can only modelled correctly as albedo and, for example, precipitation, which feeds the snow layer, are accurately represented.

For Antarctica, melt directly links to ice shelf stability. The former Larsen A, B and Wilkins ice shelves (partly) disintegrated due to hydrofracturing caused by melt water ponding (Banwell et al, 2013). Subsequently, grounded glaciers previously buttressed by these ice shelves accelerated after the disintegration (Rott et al, 2011). Recent observations shows that supraglacial meltwater is far more abundant on ice shelves in Antarctica than previously assumed (Kingslake et al, 2017; Lenaerts et al, 2016). Consequently, many ice shelves may be more vulnerable to disintegration than previously assumed, which could increase the projected mass loss of the AIS in the coming century (e.g. Fürst et al, 2016). That is why robust estimates of future melt at the surface of the AIS are an important first step to quantify the potential additional mass loss from the AIS. Similarly as for other glaciated areas, accurate estimates of melt are only possible if the physical processes that govern melt and retention are parameterized in sufficient detail.

## Research questions

As a research group we aim to provide the most accurate historical, contemporary and future SMB estimates of the GrIS, AIS and key glaciated regions on Earth. The regional climate model simulations proposed here are a continuation of research carried out recently or planned for 2018 (see 2017 and 2018 project reports). For 2019, we focus on the future SMB of the Antarctic Peninsula and the state of the three glaciated Russian archipelagos. These regions were chosen for further analysis because in the Antarctic Peninsula ice shelf disintegration has already started and its remaining ice shelves are most likely to disintegrate prior the ice shelves around the Antarctic mainland. The glaciers in the Russian Arctic will be investigated because so far they have received very little attention due to their remoteness and limited accessibility. Unlike many other glaciated regions, none or very limited in situ data are available for a first estimate of their current SMB. Although it is estimated that so far they have not provided a very large contribution to GMSLR, the glaciers and ice caps on these archipelagos are very susceptible for climate change due to their gentle slopes and low elevations. With these two simulations proposed below we aim to answer the following research questions:

- How likely is it that the remaining ice shelves on the Antarctic Peninsula will disintegrate due to enhanced melting caused by climate change during this century?
- What is the SMB of the glaciers on the glaciated Russian Archipelagos and how much has ablation increased in the past 50 years?

Furthermore, in parallel to these simulations the following more fundamental questions will be investigated:

- How much will modelled albedo and subsequently melt improve when the spectral nature of both shortwave radiation and snow albedo are taken into account?
- Will SMB estimates of rugged glaciated archipelagos improve if atmospheric flow and precipitation is modelled on O(1 km) scales?

## 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 glaciated archipelagos. To achieve this, dynamical downscaling using regional climate models (RCMs) is commonly used. In 2019, we plan to use the Regional Atmospheric Climate Model RACMO2, the firn densification models FDM and SNOWPACK and start exploring the possibilities of the HCLIM model to simulate the SMB of land ice.

### RACMO2.3p2

RACMO2 is one of the leading RCMs in this research field and has been used for numerous 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, 2016, 2017; 2018, 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.

Data from RACMO2.3p2 are postprocessed in two ways. Firstly, for Arctic glaciers, ice caps and ice sheets the surface mass balance is 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 (e.g. Noel et al, 2016). Furthermore, 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.

### 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; van de Berg et al, in preparation). 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

1. A future climate (1980-2100) run for the Antarctic Peninsula will be carried out at 8 km resolution using the RCP8.5 scenario. This simulation will be driven by the 1980-2100 RACMO2 run which in turn is by CESM2 data, which is planned to be completed in 2018. Estimated costs are typically 6 kSBU and 23 GB per month thus approximately 9 MSBU and 32 TB storage space for the full run.
2. A 5.5 km 1958-2017 climate and SMB reconstruction will be run for the three major Russian Arctic Archipelagos (Novaya Zemblya, Franz Josef Land and Severnaya Zemblya). This run will be driven by ERA5, if available in time for the full period, and otherwise complemented by ERA-40 and ERA-Interim data. After downscaling, similar detailed and good SMB results are expected as are obtained for Svalbard (Figure 1). SMB data will be combined with discharge and altimetry/GRACE observation in order to provide a full picture of the recent changes in the mass balance of these three archipelagos. Estimated costs per month are typically 12 kSBU and 38 GB per month, hence approximately 9 MSBU and 27 TB for the whole run.
3. A cost-efficient embedding of the spectral snow albedo model TARTES is currently almost completed. Following initial tests in the remainder of 2018, we plan longer runs for 2019. Eventually, a 30-year run covering the satellite era for the whole of Greenland will be performed, providing an improved estimate of past (narrowband) albedo and subsequently SMB of the GrIS, which can be evaluated against narrowband satellite observations. Estimated costs are typically 7.8 kSBU and 37 GB per month for the final test runs, and in total 4 MSBU and 18 TB of data for all these test runs.
4. In collaboration with KNMI and DMI, we aim to explore the potential of using HCLIM by performing test simulations for Svalbard. We request 1 MSBU and 4 TB of data to carry out several test runs. Firstly, using existing hydrostatic and non-hydrostatic configurations of HCLIM, differences in the modelled atmospheric circulation and precipitation patters are be analysed and compared to existing simulations with RACMO2.3p2. Moreover, the snowpack will be simulated using the snow model Crocus, which is embedded HCLIM but has not yet been tested.

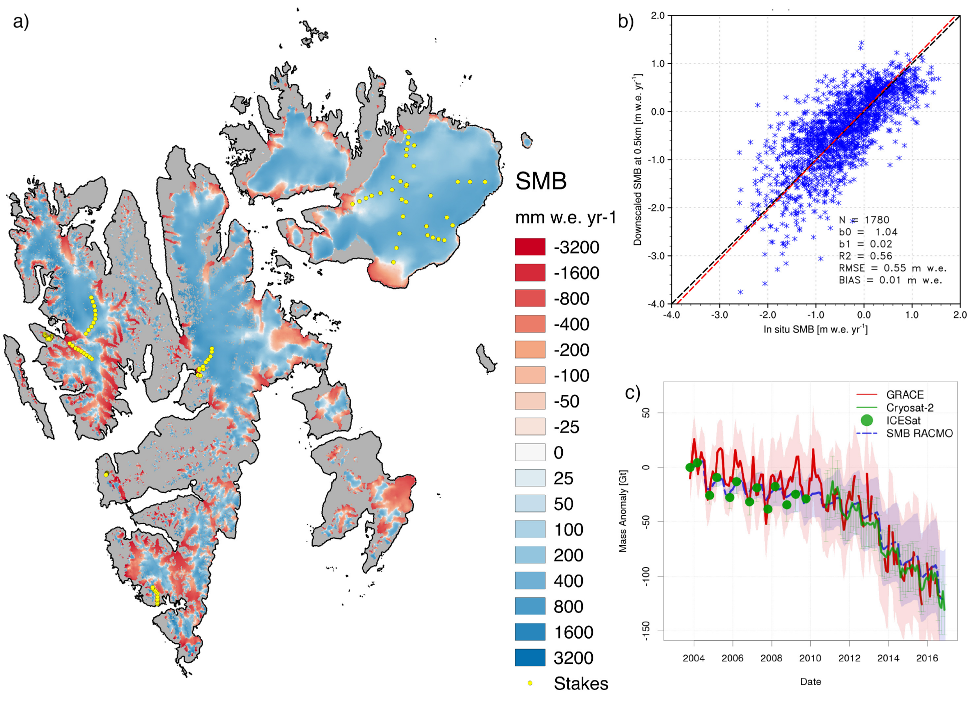


***Figure 1: a)** Mean modelled SMB (1958-2016) for Svalbard, statistically downscaled to a 500 m grid. **b)** Comparison between modelled and observed annual SMB (stakes in a) after statistical downscaling. **c)** Time series of integrated SMB comparing modelled and observational estimates from gravimetry (GRACE) and altimetry (Cryosat-2 and ICEsat).*

## Applications

- The high-resolution future climate run for the Antarctic Peninsula will be used to assess the projected increase of melt and the subsequent impact on ice shelf stability. When and where might we expect more ice shelves in the Antarctic Peninsula to disintegrate? Secondly, the run will be analysed for the current and future presence of firn aquifers in the Antarctic Peninsula. Thirdly and lastly, the simulation will improve predictions of the future contribution of the Antarctic Peninsula to GMSLR through the use of glacier models that are forced by RACMO2 model output.
- Mass loss from GIC represented the largest non-steric contribution of 20$^{th}$ century GMSL rise and is expected to provide a similar or even larger absolute contribution in the 21$^{st}$ century. So far, it is assumed that the glaciated Russian Arctic archipelagos, which hold an equivalent of about 4 cm of GMSLR, were relatively stable. However, recent satellite observations show that the glaciers on all of these archipelagos are rapidly changing due to ice dynamical processes and increasing melt. Precise estimates of their past mass balance are important to understand their dynamics and vulnerabilities and predict their potential future mass loss.
- In 2017, we have commenced the implementation of TARTES, a spectral radiation model for reflection and penetration of shortwave radiation in snow and ice, by designing a coupler that is cost-efficient without performance loss. The implantation now (mid-2018) reaches its final stage. With a narrowband radiation scheme for snow and ice, the effects of clouds, impurities and snow metamorphism on the net shortwave absorption will be modelled explicitly. Offline tests have shown significant differences with the current broadband scheme (Van Dalum et al, in preparation). It is expected that TARTES will significantly improve the modelled surface energy balance, melt rates and subsurface temperatures over glaciated regions. The proposed runs are performance tests, tuning runs and a final evaluation run. The coupling approach and the model data will be published and shared with the community. For example, the coupling approach could also be interesting for an efficient embedding of TARTES in SURFEX or in HCLIM.
- As RACMO2 is a hydrostatic model, the model resolution is downward limited to about 5 km. For most of the smooth surfaces of the GrIS and AIS, such a resolution is sufficient. However, the rugged topography of marginal areas in Greenland and the Arctic glaciated archipelagos makes 5 km insufficient for a correct representation of the atmospheric boundary layer flow and spatial precipitation patterns. Therefore, we aim to explore the performance gain by using HCLIM at O(1 km) resolution. Several other groups, e.g. DMI and SMHI use HCLIM for (sub)-arctic regions; we will share our experiences in activating Crocus as representation of glaciated surfaces.
- Besides the applications listed above, the data will be used for numerous other applications and model output will be shared with the international research community. Output of the RACMO(2) model has thus far been used in an estimated > 500 scientific publications, reports and presentations on GrIS and AIS mass balance (based on a search in Google Scholar using "RACMO **and** Greenland **or** Antarctica").

## Additional clarifications

Computer resources to execute a future climate simulation covering the Antarctic Peninsula were also requested for 2018. However, this simulation and other future climate simulations for the GrIS and AIS were obstructed by a significant delay in the development and code finalization of the envisaged forcing model CESM2. According to the original planning, CESM2 would be finalized in early 2017, but only in June 2018 was the code released (see http://www.cesm.ucar.edu/). The primary reason for this delay was that the CESM2 consortium needed many more tuning iteration steps than originally planned. As the time required for tuning an Earth System Model is poorly predictable, the expected code release date was gradually delayed from early 2017 to its final date in June 2018. This continuous process of timing changes has complicated our management of computer resources.

We decided to wait for the final version of CESM2 for two reasons. Firstly, CESM2 is expected to provide a more accurate description of current and past polar climate in comparison to many other Earth System

Models. Secondly, our research group contributed to the development of CESM2 with a focus on the improved representation of the climate of the large ice sheets.

As a result, CESM2 driven RACMO2 simulations that were planned to use the resources requested for 2017 will be carried out using resources requested for 2018. The resources requested for 2017 are partially used for other RACMO2 simulations (see final report for 2017 and progress report for 2018). As a consequence, a renewed request for computer resources is required to be able to run the climate simulations described in this document.

## 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 and Bert van Ulft at KNMI will provide additional model support for HCLIM.

## Total computational requirements

In total, the proposed runs require an estimated 23 MSBU of high performance computing facilities. As we archive model output in detail, the data storage request is significant at 93 TB. This storage is needed to allow detailed analysis of the model output at a later stage of the research.

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