SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2019
Project Title:	Present-day and future climate of Antarctica and Greenland modelled with RACMO2 and HCLIM
Computer Project Account:	SPNLBERG
Principal Investigator(s):	Dr. W. J. van de Berg
Affiliation:	Utrecht University, Institute for Marine and Atmospheric Research Utrecht (IMAU)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project:	1-1-2019
Expected end date:	31-12-2019

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	30.000.000	11.836.770	23.000.000	9.086.439
Data storage capacity	(Gbytes)	125.000	514.579†	92.000	611.422‡

† Valid for 1-1-2019.
‡ Valid for 5-1-2019. After this date, at least 100TB of data has been cleared.

Summary of project objectives (10 lines max)

The aim of the project is to facilitate regional climate model simulations with the polar adapted model RACMO2.3p2 and HCLIM. Due to limited progress in 2018, our plans as research group for 2019 with respect to heavy HPCF projects have been changed considerably. In 2019, we aim to carry out CESM2-driven historic (1950-2010) and projected climate (2010-2200) simulations for Greenland and Antarctica using the RCP8.5 and 2.6 scenarios using RACMO2 and the subsequent data postprocessing.

Furthermore, we continue our efforts to improve the representation of albedo of snow using a narrowband albedo model. Finally, we aim to explore the benefits of a non-hydrostatic model over Svalbard, i.e. glaciated mountainous regions.

Summary of problems encountered (10 lines max)

In 2019, no specific computing problems were encountered.

Summary of plans for the continuation of the project (10 lines max)

In 2019, we plan to run, analyse the CESM2-driven RCP8.5 simulations for Antarctica and Greenland. In case of fast progress and additionally available resources, a second pair of RCP2.6 simulations could be launched as well.

Within the albedo project, longer (1958-2019) simulations are planned to explore the impact of the spectral nature of albedo on recent-past snowmelt and ablation for the Greenland Ice Sheet.

It is, therefore, well possible that we need to request additional HPCF resources in 2019; in contrast to 2017 and 2018, years in which we did not use a significant fraction of the resources allocated.

List of publications/reports from the project with complete references

A short paper will be published on the CESM2-driven historical simulations of RACMO2.3p2 over Greenland. The results of the climate projections will be published in two separate papers, one on the Greenland Ice Sheet and one on the Antarctic Ice Sheet. Publications are also planned for the albedo project; these papers will have a focus on the evaluation of the modelled albedo and the subsequent impact on the modelled surface mass balance and snow processes.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

Proposed, completed and planned activities in 2019

In the project proposal, the following runs were proposed:

1) A 1980-2100 RCP8.5 climate projection for the Antarctic Peninsula at 8 km-resolution, driven by CESM2. This run is postponed until similar runs for whole Antarctica and Greenland, which were planned initially for 2017, are completed and analysed.
2) A 5.5 km, ERA5 driven 1958-2019 climate and SMB reconstruction simulation for the three major Russian Arctic Archipelagos. These simulations are cancelled for now as the accompanying research project has not been granted.
3) A 1979-2019 ERA5 driven RACMO2 simulation including a narrowband albedo model for glaciated surfaces. The implementation of this model is completed; several runs on 11 km resolution spanning about a decade have been completed so far, results will be discussed in detail below. More runs will be carried out in the second half of 2019.

4) Exploratory simulations of the non-hydrostatic regional climate model HCLIM over Svalbard have been postponed. It is intended as student research project, however so far, no student has been found to carry out this task.

The following simulations have been carried out instead – the results will be discussed below in detail:

1) Two 1950-2014 CESM2 driven simulations of RACMO2.3p2 have been completed and analysed.

CESM2-driven RACMO2 simulations for Greenland and Antarctica

In order to provide updated projections of the future climate, snowmelt and surface mass balance (SMB) of the Greenland Ice Sheet (GrIS) and Antarctic Ice Sheet (AIS), we first carried out historical simulations of RACMO2 driven by the Community Earth System Model CESM2. These simulations were setup similarly as official CMIP6 simulations, thus with fully interactive atmosphere, ocean and sea ice but with fixed land ice. As our institute is also involved in the development of CESM2 – our contribution concentrated on the representation of Greenland and Antarctica in the atmosphere model – using CESM2 boundaries is therefore a very logical choice.

After the much-delayed release of CESM2 in July 2018, in-house historical runs of CESM2 dedicated for this project were completed in the fall of 2018. At the same time, the one-way coupling of RACMO2 to CESM2 was optimized and the the 365-day calendar employed by CESM2 was implemented. At the end of 2018, the coupling between CESM2 and RACMO2 was assessed to be error-free and final historical simulations (1950-2010) with RACMO2 for both the GrIS and AIS were commenced.

These historic simulations are now completed and analysed and the results are very good. As CESM2 does not resemble the past synoptic weather, it only makes use of the observed aerosol loads from volcanic and anthropogenic emissions, so that fully one-to-one match cannot be expected. Nevertheless, the CESM2-driven RACMO2 simulation for Greenland closely resemble the observed climate (not shown) and SMB (Fig. 1). For accumulation, using observations that are always multi-year climatological values, RACMO2.3p2-CESM2 is even slightly better than RACMO2.3p2-ERA (Fig 1b). For ablation, for which primarily annual observations were used, the RMSE of RACMO2.3p2-CESM2 is modestly higher. Nevertheless, as the other statistics are near-similar, this evaluation shows that RACMO2.3p2-CESM2 successfully resembles the spatial SMB patterns. And even though RACMO2.3p2-CESM2 follows its own synoptical pathway, it models the onset of decreasing SMB around 1990, similar as observed in reality. A paper on the results for Greenland will be submitted soon.

Figure 2 shows the discharge basin integrated SMB for Antarctica as estimated by RACMO2.3p2 driven by ERA-Interim and CESM2. As both simulations resemble the strong accumulation gradients over Antarctica, integrating the SMB over basins gives a better overview of regional shifts of SMB. Indeed, Figure 2 shows that CESM2 induces a shift of accumulation to Dronning Maud and Enderby Lands (0 to 70 °E), on expense of Wilkes Land (80 to 130 °E) and West Antarctica (60 to 150 °W, South of 70 °S. In the CESM2-driven run, upper air temperatures are 1-2 K lower in the Indian and Pacific sectors of Antarctica and the surrounding oceans. Furthermore, the circulation is more onshore in Dronning Maud land while in Wilkes land, the circulation is more offshore. These two changes explain the shifts and general decrease of the SMB over Antarctica. In line with the upper air temperature changes, higher snowmelt rates are modelled in the CESM2-driven run for the ice shelves on the Eastern side of the Antarctic Peninsula and in Dronning Maud Land, while less snowmelt is modelled for the other ice shelves surrounding Antarctica.

Even though RACMO2.3p2 driven by CESM2 fails to mimic the current climate and SMB patterns without discernible differences, we concluded that RACMO2.3p2 driven by CESM2 provided an adequate enough representation of the Antarctic climate to use this model combination for future climate projections under different emission scenarios.

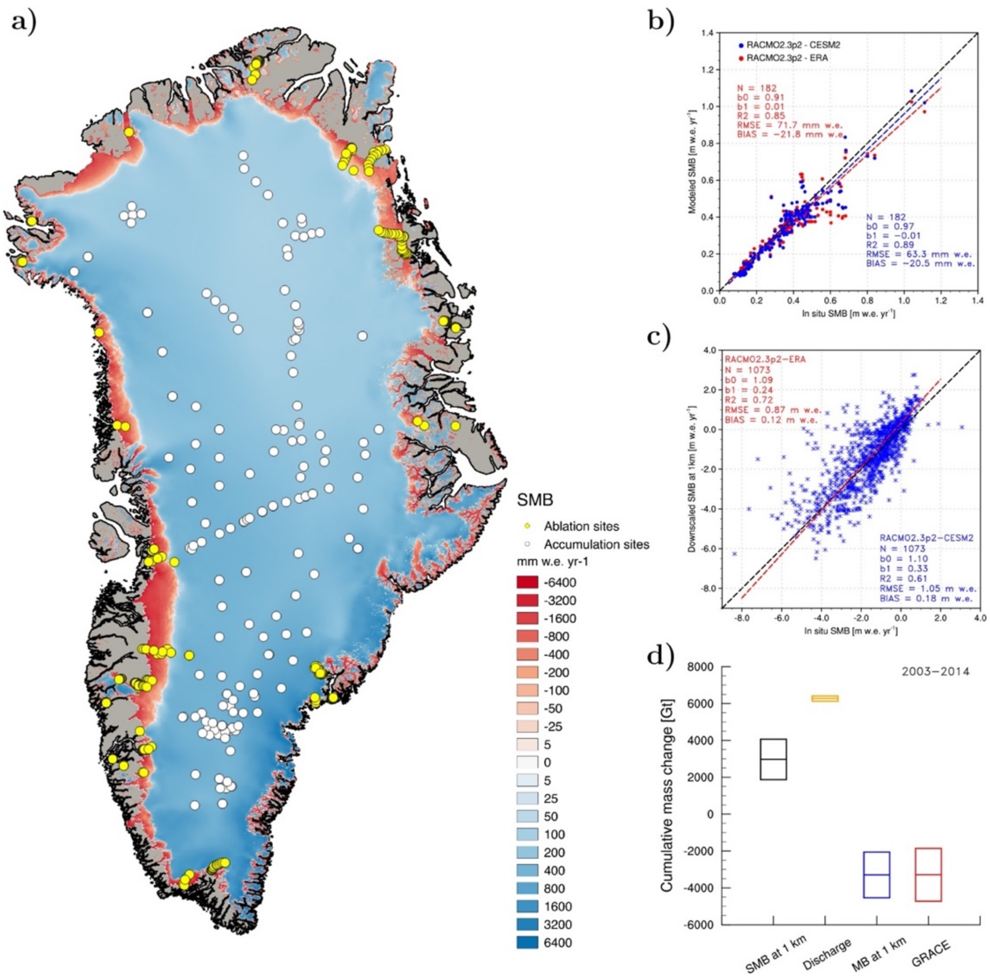

Figure 1: ***(a)*** *Annual mean surface mass balance (SMB) of the Greenland Ice Sheet and peripherical glaciers as modelled by RACMO2.3p2 driven by CESM2 for 1950-2014 model climate forcing, statistically downscaled to 1 km resolution. Comparison of modelled and observed SMB at* ***(b)*** *182 accumulation sites (white dots in Fig.1a) and* ***(c)*** *213 ablation sites (yellow dots in Fig. 1a). Figure 1b compares accumulation from the ERA-driven 11 km (red dots) with the CESM2-driven 11 km (blue dots) simulation of RACMO2.3p2; regression lines (dashed) and statistics, i.e. number of observations (N), regression slope (b0), intercept (b1), determination coefficient (R2), RMSE and bias, are displayed for the ERA-froced (red) and CESM2-forced (blue) simulations. Figure 1c also displays regression line (red dashed line) and associated statistics for the ablation zone. For clarity, modelled ablation from the ERA-driven simulation is left out in Fig. 1c.* ***(d)*** *Comparison of the mass balance (MB) being SMB minus ice discharge (Mouginot et al., 2019) with a remote sensed estimate of the MB (GRACE; Wouters et al., 2013).*

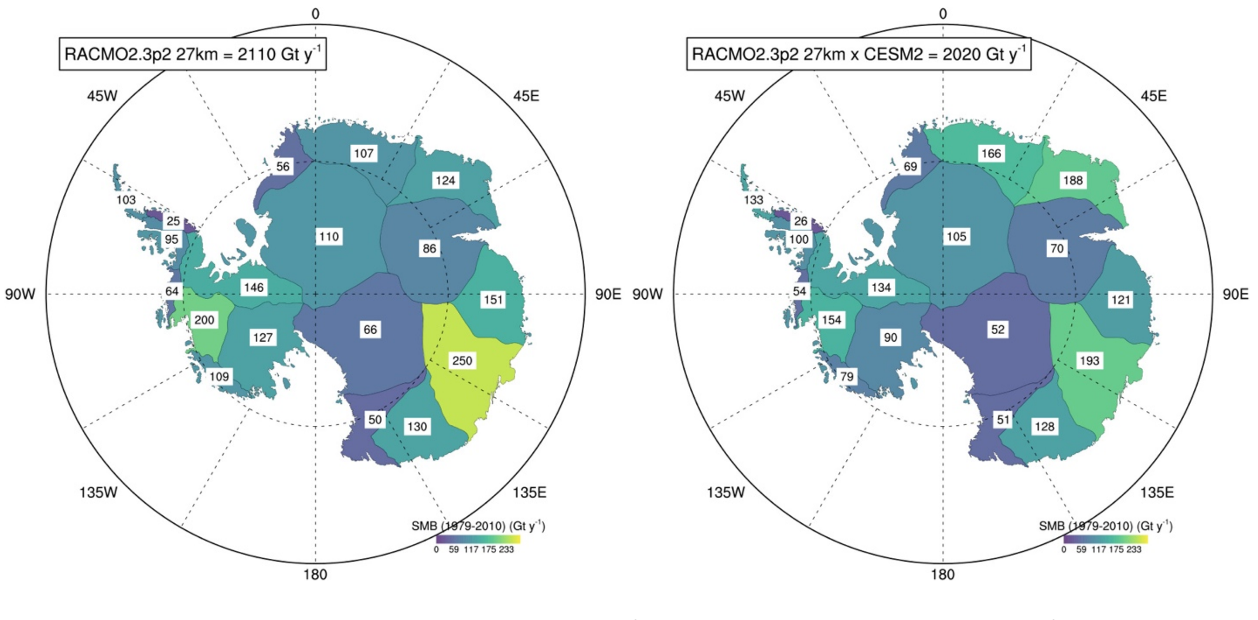

Figure 2: *Mean annual SMB basin-integrated for 1950-2010 for* ***a)*** *RACMO2.3p2 driven by ERA-Interim and* ***b)*** *RACMO2.3p2 driven by CESM2. One Gt equals 10^{12} kg, thus 1 km^3 of water.*

Implementing a narrowband albedo model in RACMO2

Over glaciated surfaces, the albedo (surface reflectivity for shortwave radiation) is the key process to model right as it acts in powerful positive feedback processes within the surface energy balance. The albedo over glaciated surfaces ranges from 0.9 for fresh, fine grained snow; 0.7 for old, previously melted snow to values around 0.4 for bare glacial ice. Snow metamorphism, snow melt and subsequent refreezing cause the gradual decrease of the albedo of snow, until all snow has been melted away and glacial ice surfaces. As the rate of the albedo decrease increases with the amount of absorbed solar radiation, the albedo-melt and the albedo-snow metamorphism are both very strong positive feedbacks. Hence, a small error in the snow albedo could lead to very different melt and meltwater runoff rates later in the season.

RACMO2.3p2 included already a sophisticated but broadband snow grain size based broadband albedo, but a broadband albedo cannot physically represent the counteracting effects of clouds, solar zenith angle, vertical grain size profile and impurity load on the spectral albedo and incoming spectral radiation distribution. Besides that, radiation penetration, which leads to significant subsurface heating and melt, was not yet included. With the implementation of the spectral snow albedo model TARTES using a novel coupler, the spectral nature of irradiation and snow albedo as well as radiation penetration are explicitly modelled.

Figure 3 shows typical albedo values for 27 July, the peak of the melting season. With the new model, slightly higher values are modelled for the dry snow zone (marked with 1 in Fig. 3a) but slightly lower albedos in snow covered zones with regular melt, like around the South Dome, marked with 2. A much sharper albedo transition is modelled in the lower percolation zone (marked with 3); we currently investigate if this is physically correct or a model artefact. In the ablation zone, modelled albedos are slightly higher as now the impact of clouds on the broadband albedo of ice is included.

Figure 3c shows that both the novel and current albedo scheme in RACMO2.3p2 give higher albedo estimates then observed by remote sensing. Most of the difference is due to fact that MODIS albedo is for clear sky only, while the model albedos are all-sky albedos. Clouds filter out the longer wavelengths of the incoming spectrum, for which the spectral albedo of snow is lower, and therefore increase the broadband albedo of snow. If modelled clear-sky albedos are compared, the differences between modelled and remotely sensed albedo become much smaller (not shown). Still, the evaluation is not entirely precise as the solar zenith angle, not known in the time-blended MODIS product, does affect the broadband albedo. Therefore, we aim to evaluate the albedo model by comparing modelled with measured narrowband albedos on the various intervals of the MODIS sensor. In this manner, uncertainties introduced by the narrowband to broadband conversion of remote sensed albedo are circumvented. It is planned that the final simulations are carried out in the coming months.

References:

Mouginot, J., E. Rignot, A. Bjørk, M.R. van den Broeke, R. Millan, M. Morlighem, B.P.Y. Noël, B. Scheuchl. And M. Wood, 2019: Forty six years of Greenland Ice Sheet mass balance from the component method: 1972 to 2018, *PNAS*, **116** (19), 9239 - 9244, https://doi.org/10.1073/pnas.1904242116.

Wouters, B., J.L. Bamber, M.R. van den Broeke, J.T.M. Lenaerts, I. and Sasgen, 2013: Limits in detecting acceleration of ice sheet mass loss due to climate variability, *Nature Geoscience*, **6**, 613 - 616, https://doi.org/10.1038/ngeo1874.

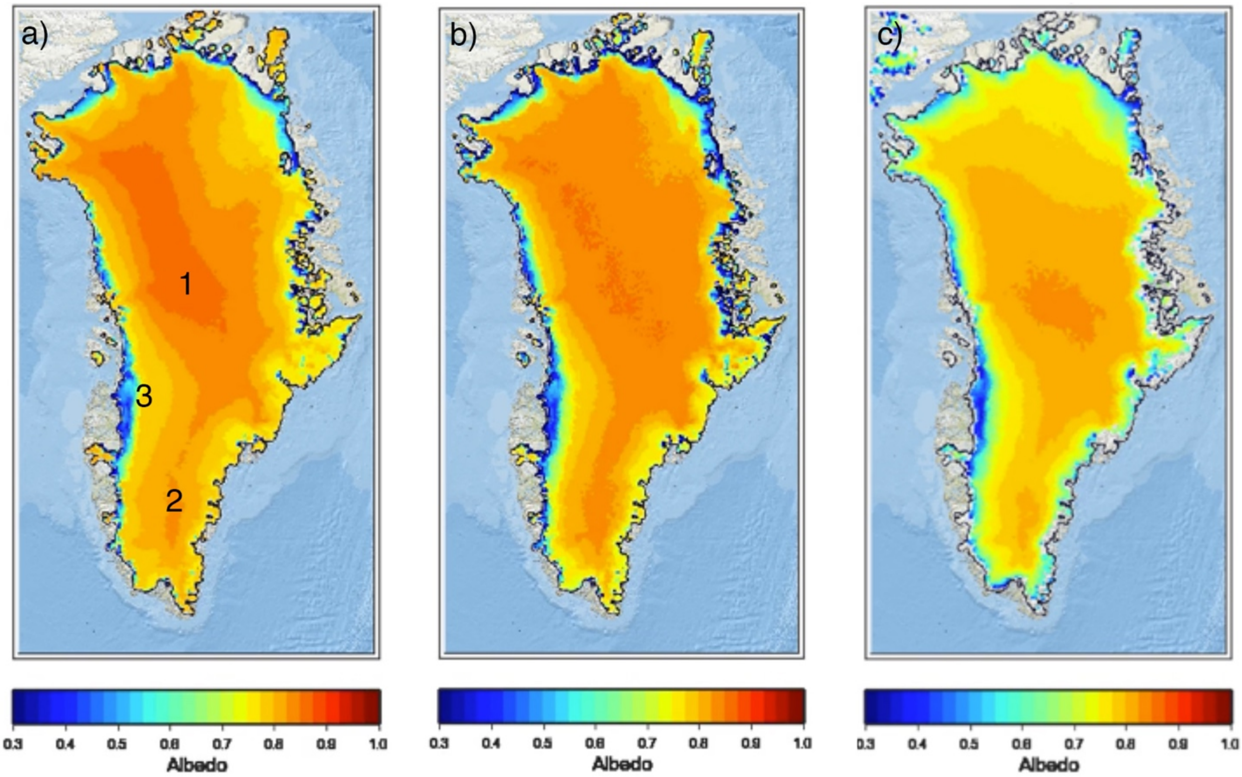

Figure 3: *Modelled broadband all sky albedo by **a)** the updated version of RACMO2 incorporating the narrowband albedo model and **b)** RACMO2.3p2, the operational version of RACMO2. **c)** Remote sensed clear-sky diffuse albedo by MODIS. As MODIS albedos are provided as a 16 day running mean over available images, RACMO2 albedos have been postprocessed equivalently. Shown are the 2006-2012 mean value valid for 27 July. The numbers 1 to 3 are discussed in the text.*