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	2020
Project Title:	Regional climate modelling of Greenland and Antarctica
Computer Project Account:	spnlberg
Principal Investigator(s):	Dr. Willem Jan 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:	1-1-2020
Expected end date:	31-12-2020

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)	33.000.000	33.816.401	20.000.000	10.956.427[1]
Data storage capacity	(Gbytes)	92.000	590.000[2]	120.000	690.000[3]

[1] As for 20 June 2020
[2] Valid for 1 January 2020
[3] As for 10 June 2020

Summary of project objectives (10 lines max)

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, therefore we the polar adapted version of the regional atmospheric model RACMO2, version 2.3p2.

In 2020, 1) we focus on using an improved representation of snow albedo, 2) updating operational estimates of the climate and surface mass balance of the two ice sheets using ERA5, and 3) deriving projections of the climate and surface mass balance of the two ice sheets.

Summary of problems encountered (10 lines max)

No major problems were encountered.

Inconvenient is by times to slow response of the scratch disks at the HCPF machines in interactive use and slow retrieval of files from ECFS.

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

For the remainder of 2020 we plan:

1. Completion simulations for Antarctica with the updated version of RACMO, version 2.3p3, on moderate resolution (27 km) for 1979-2019.
2. Completion of renewed operational historical simulations of RACMO, version 2.3p2, driven by ERA5, for both ice sheets on the highest feasible resolutions (5.5 km for Greenland, 11 km for Antarctica). Both simulations are started in 1990. Surface mass balance (SMB) estimates for the Greenland Ice sheet will be subsequently statistically downscaled to 1 km.
3. Performing projections of the future climate and SMB for Greenland and Antarctica using scenario SSP1-2.6 and driven with CESM2 boundary files. The simulation for Greenland is only possible if additional budget is granted.

Our plans for 2021 are described in our special project proposal for 2021.

List of publications/reports from the project with complete references

A publication is planned for:

- The CESM2 driven SSP5-8.5 2015-2100 projection for Antarctica.
- The Antarctic simulations using RACMO2.3p3.
- The efforts to improve the firn densification model FDM.

A publication is under consideration for:

- The new operational climate and SMB estimates for Antarctica, as this 11 km resolution is unprecedented for this kind of datasets.

No separate publication is foreseen for

- The updated operational climate and SMB estimates for Greenland.

However, it is expected that these two operational simulations, which are freely available for other research groups, will be used in numerous publications in research groups world-wide, similar to the usage of our current operational climate and SMB products.

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.

Improved physical representation of snow and ice albedo

In 2019, the development of RACMO2, version 2.3p3, has been completed and this version was successfully applied for the Greenland Ice Sheet. In 2020, we have started applying this updated version for the Antarctic Ice Sheet.

It turns out that initial version of RACMO2.3p3 produces undesirably high temperatures compared to the previous version RACMO2.3p2 (Figure 1a) and observations (not shown) due to a too low summer snow albedo (Figure 1b). Therefore, we have to spend computational time to tune the dry and wet snow metamorphism in RACMO2.3p3 to Antarctic conditions to generate more realistic results (Figure 1c). We have succeeded in removing the biases in the interior of Antarctica. Still, significant temperature changes are observed in the ice shelves of Dronning Maud Land and the Amery ice shelf and for all ice shelves except for the Ross and Filchner-Ronne ice shelves, the modelled snow melt is above observational estimates.

Currently, we assess the physical mechanisms causing these deviations in order to further improve the performance of RACMO2.3p3. It is expected that this analysis will lead to a final Antarctic version of RACMO2.3p3, which will be used in a final simulation within this project. The results of this simulation and the preceding simulations will be used in a publication to be completed in 2020 or 2021.

Renewal of the operational climate and SMB estimates using ERA5.

In preparation to use ERA5 boundaries for our operational historical estimates of the climate and SMB of Greenland and Antarctica, we first prepared, tested and evaluated the impact of using 3-hourly ERA5 data as boundary files instead of 6-hourly data as we did for ERA-Interim. This impact was minor but slightly positive. Hence, we choose to use 3-hourly ERA5 data and not hourly data, as the latter would be very cumbersome due to vast amount of data required to drive RACMO2, while the benefit would be very limited.

For Greenland, we first extended our operational ERA-Interim forced data set from 1 September 2019 until the end of 2019. In order to balance between gained performance by using ERA5 and computational expenses, we renewed our operational simulation from 1990 onwards using ERA5. This simulation is currently ongoing. Once the backwards extension of ERA5 is completed or either a fundamentally improved version of RACMO2 is available, we will rerun RACMO2 for Greenland for the whole extend of ERA5.

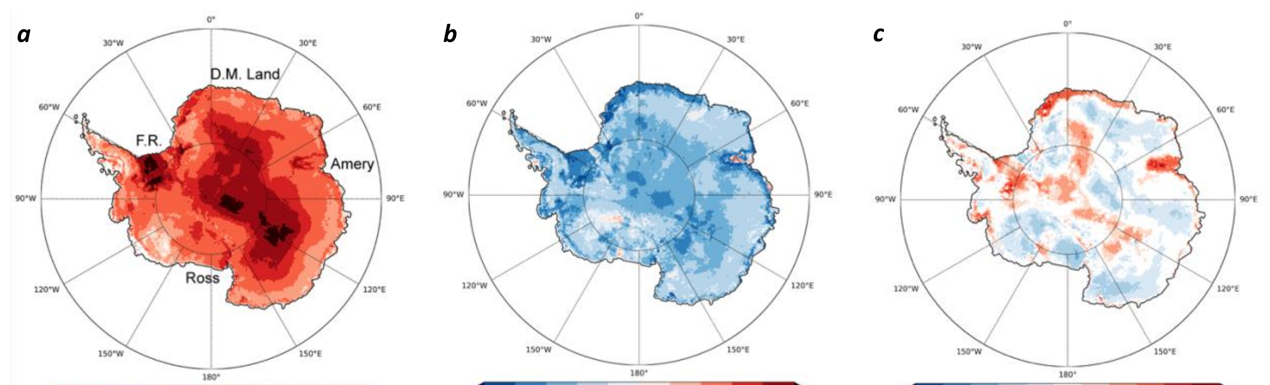

Figure 1. *Monthly-averaged differences between RACMO2.3p3 and RACMO2.3p2 for January 1980 for* ***a*** *skin temperature, and* ***b*** *broadband albedo.* ***c*** *Monthly-averaged skin temperature difference between a tuned version of RACMO2.3p3 and RACMO2.3p2 for January 1980. Geographical locations are shown in panel a, with abbreviations for Filchner-Ronne (F.R) and Dronning Maud Land (D.M. Land).*

For Antarctica, we also first extended our operational ERA-Interim forced data set, which employs a resolution of 27 km, from 1 September 2019 until the end of 2019. Next, we prepared to set to an improved resolution of 11 km, which allows to resolve the steep margin of the Antarctic Ice Sheet in much more detail. These initial test are completed, currently the operational simulation is in production. Again, in order to balance performance gain and computational costs, this ERA5 driven 11 km simulation is initiated in 1990.

A 2015-2100 projection of Antarctic climate and SMB under a high warming scenario.

In 2020 we carried out the majority of the simulation of this projection, using the SSP5-8.5 scenario and CESM2 boundaries. Figure 2 shows integrated SMB estimates from this historic simulation (blue), projection (red), and the previous ERA-Interim forcing (black, 1979-2018) for the Antarctic Peninsula, West and East Antarctic ice sheets, and the Antarctic ice sheet (AIS) as a whole. Our results show that the SMB increases steadily in the 21st century, as a result of increasing precipitation. However, a very significant increase in melt water production is observed, up to 1360 Gt a^{-1} for 2090-2100, compared to 264 Gt a^{-1} as modelled for 1950-1980. Finally, the RACMO2.3p2 simulation driven by CESM2 simulation compares well to the RACMO2.3p2 simulation driven by ERA-interim simulation, when averaged over the AIS (not shown). A paper on these results is currently in draft.

Evolution of the firn layer of the Greenland Ice Sheet

RACMO2 is equipped with a detailed physical firn model. However, there are several benefits for operating a stand-alone firn model alongside. First, the vertical resolution for buried snow and ice layers can be larger, improving accuracy. Second, a stand-alone firn model allows for spinning up the model to a more accurate equilibrium state. And third, a stand-alone model enables us to perform cost- and time-effective model development. Therefore, the vertical firn profiles are refined using the firn densification model FDM, which has a higher resolution than the snow model in RACMO2 and therefore gives a more accurate estimate of melt water retention and refreezing (Steger et al, 2017; Ligtenberg et al, 2018). In particular, the formation of impenetrable ice slabs on the firn of the Greenland Ice Sheet has received increased attention: they lead to reduced water buffering capacity and enhanced runoff of meltwater into the ocean.
In 2020, we will update the model parameterizations, and conduct a historic simulation of the firn layer at Greenland in order to investigate the formation of impenetrable ice slabs. The model will be forced by ERA5 or ERA-Interim. Subsequently, the evolution of ice slabs in the future will be investigated with a future run, using CESM2 output as forcing for the firn model.

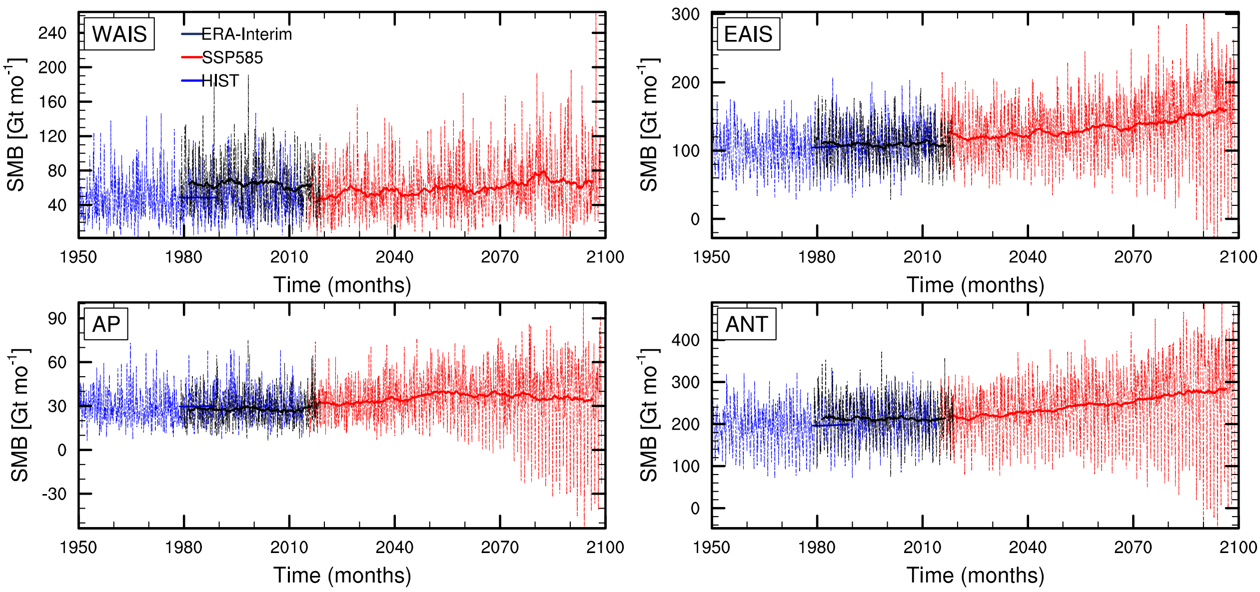

Figure 2: Integrated SMB for WAIS, EAIS, AP and the AIS. Monthly values are shown in Gt per month, with a 5 year running mean in bold.

References:
Ligtenberg, S.R.M., P. Kuipers Munneke, B.P.Y. Noël and M.R. van den Broeke, 2018: Brief communication: Improved simulation of the present-day Greenland firn layer (1960-2016), *The Cryosphere*, **12**, 1643-1649.
Steger, C.R., C.H. Reijmer and M.R. van den Broeke, 2017: The modelled liquid water balance of the Greenland Ice Sheet, *The Cryosphere*, **11**, 2507-2526.