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	2021
Project Title:	The contemporary and projected climate of Greenland and Antarctica
Computer Project Account:	SPNLBERG
Principal Investigator(s):	Dr. W.J. van de Berg
Affiliation:	Utrecht University, The Netherlands
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project:	1 January 2021
Expected end date:	31 December 2021

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[a]	28.814.901	30.000.000	17.910.936[b]
Data storage capacity	(Gbytes)	120.000	867.074[c]	200.000	964.413[d]

[a] 20.000.000 was the initial allocation; in October 10.000.000 extra resources were requested and granted.
[b] As for 22 June 2021
[c] Data storage on 31 December 2020
[d] As for 10 June 2021

Summary of project objectives (10 lines max)

This projected aims to provide a) operational baseline estimates of the climate and surface mass balance (SMB) of the two ice sheets and adjacent glaciers; b) projections of mass loss from surface processes from these ice sheets; c) operational estimates of the thickness of the firn layer over these ice sheet; and finally, d) improve the representation of the physical processes in our models to the latest knowledge.

Summary of problems encountered (10 lines max)

No major issues. The problem with accessing files from ECFS, which occurred in the fall of 2020, have not reoccurred.

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

For the remainder of 2021, our plans are

- Carry out two or three updates of our operational estimates of the climate and SMB of the two large ice sheets.
- Complete a CESM2 driven RACMO2p3.2 projection for the scenario SSP2-4.5 for the Greenland Ice Sheet.
- Update the baseline estimates of the evolution of the firn layer over the two ice sheets since 1957 (Greenland) and 1979 (Antarctica).
- Continue with the numerical development of RACMO2.4, which employs IFS physics of cycle cy47r1.

List of publications/reports from the project with complete references

A list of recent publication from SPNLBERG projects is provided in the final report for 2020.

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.

In order to reach our aims, we have carried out the following numerical experiments in 2021:

Up-to-date operational climate and SMB estimates.

In 2021, we have updated our operational estimates for Antarctica and Greenland to 1 March 2021, the end of the austral summer and Northern Hemisphere winter. A next update is planned for after either 1 September or 1 October, the end of the Northern Hemisphere summer, but may be carried out earlier if updated data is requested.

Future climate projections

In the past two years, we have renewed our projections using an updated model version, RACMO2.3p2, and new, CMIP6 based CESM2 boundary conditions. In 2021, we have added a projection following RCP SSP1-2.6 for the Greenland Ice Sheet, and rerun the projections for the Antarctic Ice Sheet as we detected a minor but significant version inconsistency in the projections derived in 2020.

Strong mitigation scenario projection for Greenland

In 2021, we conducted an additional scenario projection of the GrIS SMB using RACMO2.3p2 at 11 km forced by CESM2 at ~100 km under a low-end warming scenario (SSP1-2.6) for the period 2015-2100 (see cyan line in Fig. 1). The latter projection was statistically downscaled to 1 km spatial resolution. This run complements our previous SMB reconstruction (1950-2014) and projection (2015-2100) under a high-end emission scenario (SSP5-8.5) that were published in Noël et al. (2020b, TC) and Noël et al. (2021a, GRL) (see red line in Fig. 1). To sample other potential warming trajectories in the course of the 21st century and beyond, we statistically downscaled all available 100 km CESM2 climate reconstructions (1850-2014) and future projections (2015-2300; including SSP1-2.6 to SSP5-8.5) to a 1 km grid. This data set consists in 47 runs that span 450 years (see Fig. 1). Among these runs, one accounts for glacier dynamics (i.e. glacier thinning/retreat and elevation feedbacks). These new data sets will be extensively used by international collaborators investigating projected mass loss, sea level rise contribution, glacier dynamics and thinning of the GrIS, and are the core of two manuscripts in preparation. Topics include: 1) study of the GrIS SMB variability throughout the 21st century; 2) identification of future tipping points for the GrIS mass loss.

Projections for Antarctica

The initial plan for 2021 was to add a CESM2-driven projection following SSP1-2.6 to the CESM-2 driven historical and SSP5-8.5 simulations carried out in 2020. However, the first decades of the SSP1-2.6 simulation showed deviations between the modelled melt in the new and older simulations. After careful data and code analysis, it was found that the 2020 CESM2-driven simulations have used an incorrect code version. Given the manageable computational costs of these simulations, we decided to rerun all CESM2-based simulations with the correct code.

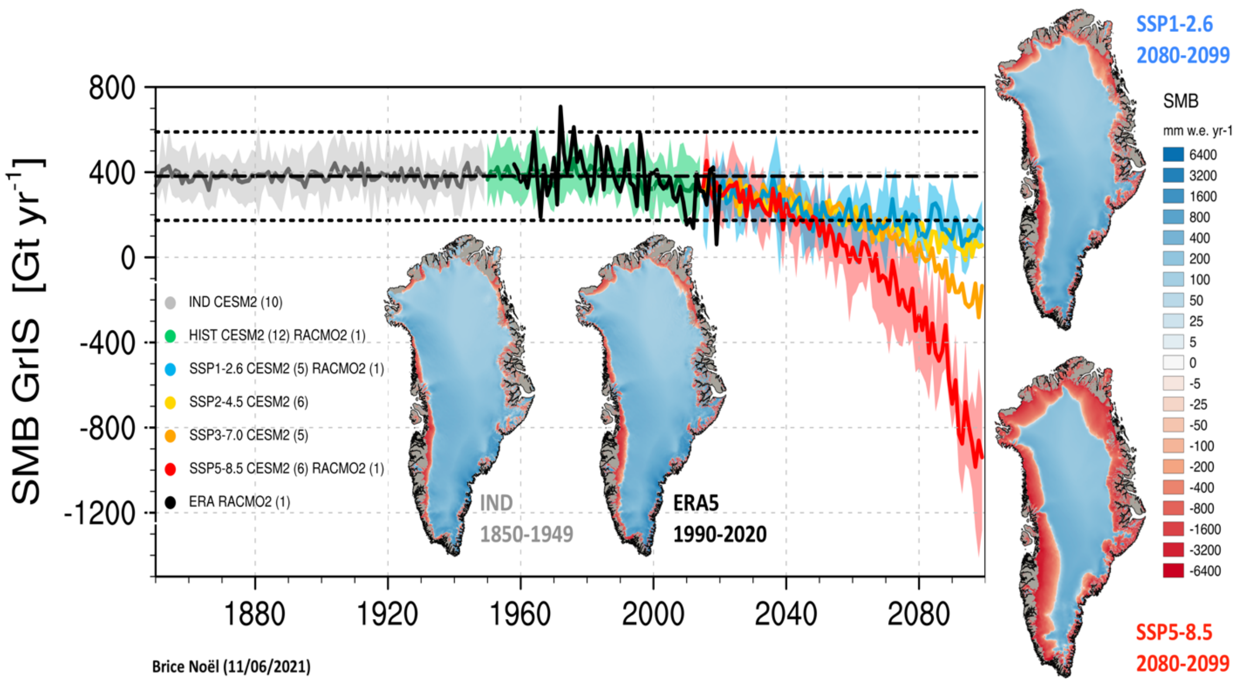

Figure 1: *Time series of Greenland ice sheet (GrIS) integrated surface mass balance (SMB) for the period 1850-2100. RACMO2.3p2 at 1 km forced by ERA40 (1958-1978), ERA-Interim (1979-1989) and ERA5 (1990-2020) is shown in black. Coloured lines represent ensemble means of multiple CESM2 runs statistically downscaled to 1 km for the periods: industrial (1850-1949; grey), historical (1950-2014; green), projections (2015-2100) under SSP1-2.6 (cyan), SSP2-4.5 (yellow), SSP3-7.0 (orange) and SSP5-8.5 (red) scenarios. The SSP1-2.6 and SSP5-8.5 ensembles include the RACMO2.3p2 projections, forced by CESM2, and statistically downscaled to 1 km. The number of members per ensemble is listed in brackets in the legend. Coloured bands show the range of individual members. Inset maps show SMB averaged for the industrial pe riod (IND; 1850-1949), the present-day (ERA5; 1990-2020) and scenario projections (SSP; 2080-2099) by the end of the 21st century (SSP1-2.6 top, SSP5-8.5 bottom).*

Figure 2 summarizes the results of these renewed simulations. It shows firstly that RACMO2 driven by CESM2 gives a very similar representation of the Antarctic climate (not shown) and SMB compared to the ERA5 driven RACMO2 simulation. Regionally differences in precipitation are visible, for example, the CESM2 driven simulations have less precipitation over West Antarctica and slightly more over East Antarctica compared to the ERA5 driven simulation. We concluded that RACMO2 driven by CESM2 will provide realistic projections for a given scenario.

Figure 2 also shows the projections for the Antarctic SMB and its components for the scenarios SSP1-2.6 and SSP5-8.5. A rather different evolution of the climate and SMB of the Antarctic Ice Sheet is projected for these two scenarios, as shown in Figure 6. For SSP5-8.5, the SMB of the grounded ice sheet is projected to increase up to 3000 Gt per year in 2100, as precipitation increases more than

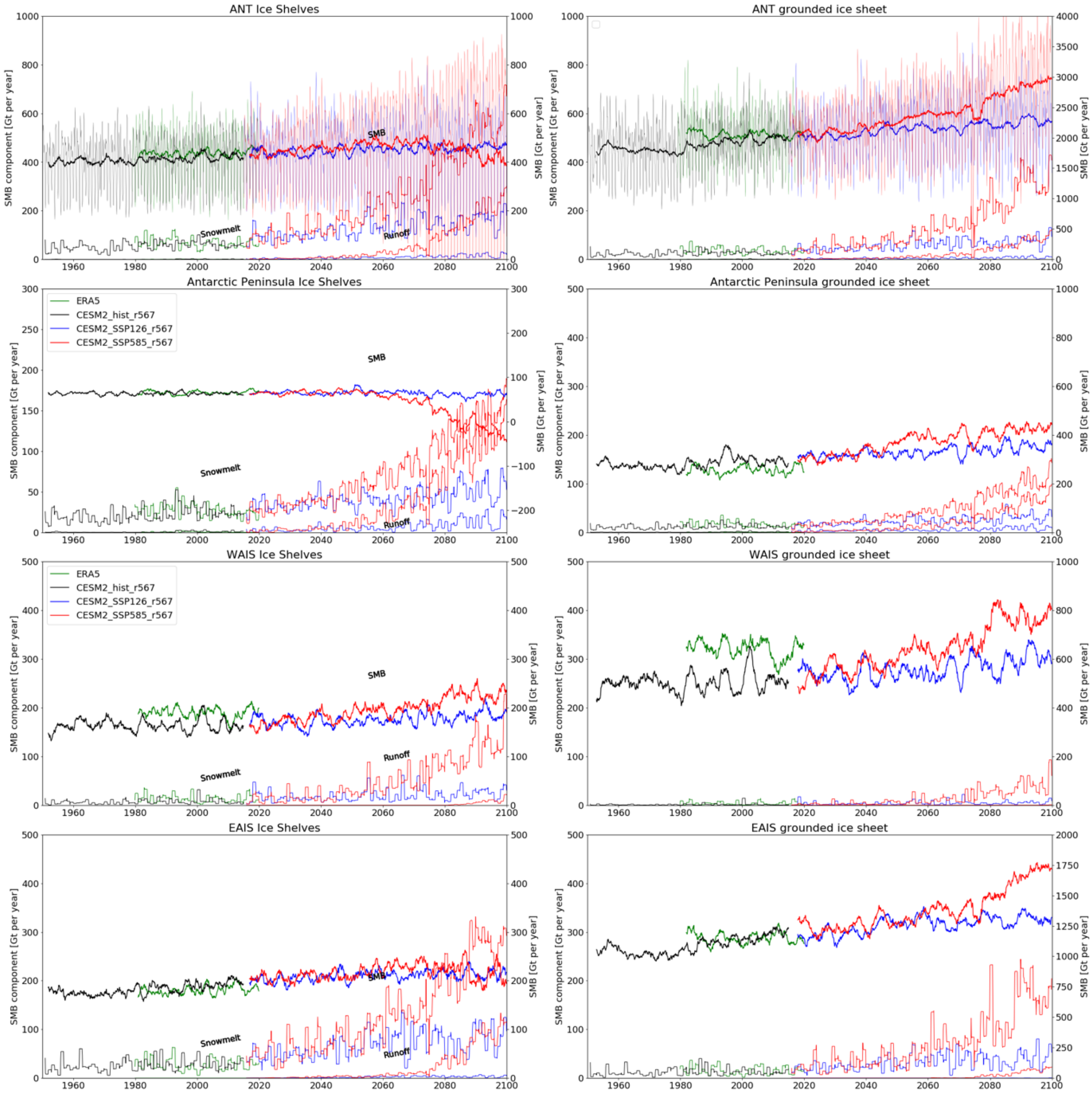

***Figure 2**: Yearly average SMB, snowmelt and runoff for Antarctica (first row), the Peninsula (second row), West Antarctica (third row) and East Antarctica (4th row), subdivided in the ice shelvse (left column) and the grounded ice sheet (right column). The ERA5 driven RACMO2 estimate of the recent past is drawn in green in all panels; CESM2 driven RACMO2 estimates of the recent past and under scenarios RCP SSP5-8.5 and SSP1-2.6 are drawn in black, red and blue, respectively. The spatially integrated SMB is displayed on the right vertical axis of a panel; snowmelt and runoff on the left vertical axis. In the upper row, monthly values are displayed with thin lines.*

meltwater runoff. Only a minor increase of the SMB is projected for RCP1-2.6. Over the ice shelves, a significant increase of surface melt is projected. For SSP5-8.5, as a result runoff becomes a significant contribution to the SMB. As abundant meltwater, required to initiate runoff, has also been identified as a cause for ice shelf break-up, these results indicate that under SSP5-8.5 many Antarctic ice shelves may disappear. This, in turn, could lead to increased ice discharge to the ocean and unstoppable mass loss of the Antarctic Ice Sheet. Such dramatic increase of melt and runoff over the ice shelf is not modelled under SSP1-2.6, showing that GHG mitigation measures have a significant effect on the contribution of the Antarctic Ice Sheet to sea level changes. Please note that shown here is the SMB only, the largest uncertainties of the contribution of the Antarctic Ice Sheet to sea level rise is by changes in ice discharge, which is not modelled by RACMO2.

Operational estimates of the firn layer evolution

Even though 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 model IMAU-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. In order to refine our operational and projected estimations of changes in the firn column, we use the firn densification model IMAU-FDM.

Greenland Ice Sheet

In 2020, using a newly available parameterization of heat conduction, an extended observational dataset of firn properties, and updated surface boundaries from RACMO2, the IMAU-FDM is retuned to improve its performance. Using this updated model version, a historic simulation of the firn layer at Greenland is currently being conducted. The goal is to investigate the representation of water processes in firn and the evolution of firn aquifers (perennial liquid water at typically 15 to 50 m below the surface) and percolation-blocking sub-surface ice lenses in a warming climate. In particular, pronounced inland extension of the regions with sub-surface ice lenses would imply that the melt water buffering capacity of the GrIS to increasing melt is less than previously thought.
The model is forced with surface boundary conditions from RACMO2, which is forced by ERA5 / ERA-Interim. Once this is done the evolution of ice slabs in the future will be investigated with a future run, using CESM2 forced RACMO output as forcing.

Antarctic ice sheet

After updating IMAU-FDM with a focus for Greenland, this new version is now also applied for the Antarctic Ice Sheet. Due to the empirical nature of some of the parameterizations and the different climatological situation of Antarctica, retuning of some empirical relations was necessary. The retuned relations are those for the densification rate of snow and the density of fresh snow. The new simulations use surface boundaries from RACMO2.3p2 forced by ERA5, instead of RACMO2.1 forced by ERA-Interim. Furthermore, the dataset of observations is extended with observations from, for example, Montgomery *et al*, (2018), and comprises now 95 locations (Fig. 3).
After the retuning phase, which has been completed early June, IMAU-FDM will be run whole Antarctica on moderate resolution and the Antarctic Peninsula on high resolution.

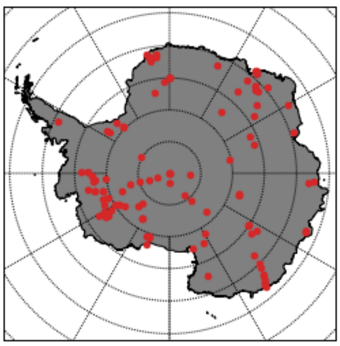

Figure 3: *Location of observations available for the evaluation of IMAU-FDM.*

Updating RACMO2 code using IFS cycle cy47r1

In February 2021, our research group got licensed access to physical process parameterizations of IFS cycle cy47r1, to update RACMO2, which operational versions now use IFS cycle cy33r1. Code implementation is ongoing, it is expected that in the course of 2021 the first test simulations with RACMO2.4 will be carried out.

References

Montgomery, L., Koenig, L., and Alexander, P.: The SUMup dataset: compiled measurements of surface mass balance components over ice sheets and sea ice with analysis over Greenland, Earth Syst. Sci. Data, 10, 1959–1985, https://doi.org/10.5194/essd-10-1959-2018, 2018.