SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Present-day and future climate of Antarctica and Greenland modelled with RACMO2 and HCLIM
Computer Project Account:	spnlberg
Start Year - End Year :	2019 - 2019
Principal Investigator(s)	Dr. W. J. van de Berg
Affiliation/Address:	Utrecht University, Institute for Marine and Atmospheric Research Utrecht (IMAU)
Other Researchers (Name/Affiliation):	Christiaan van Dalum, Stan Jakobs, Brice Noël, Melchior van Wessem (All UU/IMAU)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The aim of the project is to facilitate regional climate model simulations with the polar adapted regional atmospheric climate 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

(If you encountered any problems of a more technical nature, please describe them here.)

In 2019, no major technical hurdles were experienced. Minor, and solved technical hurdles were the adaptation of RACMO2 to a 365 day calendar and the disappearance of an important dataset on ECFS.

Computationally, the initially requested resources for 2019 appeared to be insufficient; in October 10 MSBU additional HPCF resources were requested and granted. Nonetheless, some plans for 2019 had to be postponed to 2020.

As no master student of our university showed interest in the project, the planned non-hydrostatic explorational experiments over Svalbard using HCLIM could not been carried out.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The application and reporting procedure are clear and concise. The only inconvenient aspect is the rather early deadline for applications. By June, it is rather hard to estimate the computational goals and resources needed next year as those depends, among other things, on the progress made in the running year.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

Planned and completed activities in 2019

In the project proposal, the following experiments were proposed:

1. A 1980-2100 simulation with RACMO2, covering the Antarctic Peninsula at 8 km resolution following the SSP5-8.5 scenario. *This simulation has not been carried out due to delays in the delivery of CESM2 and computational constraints.*
2. A 1958-2017 ERA5 driven simulation with RACMO2 at 5.5 km covering the three major Russian Arctic Archipelagos (Novaya Zemblya, Franz Josef Land and Severnaya Zemblya). *This simulation has not been carried out due to shifted research ambitions and computational constraints.*
3. Longer decadal reanalysis driven simulations covering the Greenland Ice Sheet using an updated version of RACMO with embedded the spectral snow albedo model TARTES. *These simulations have been carried out and will be discussed below.*
4. Explorational HCLIM simulations over Svalbard. *These simulations have not been carried out due to lacking man power.*

In the proposal for additional computational resources, the following experiments were proposed:

5. Two additional simulations covering 1979-2018 to assess the melt-albedo feedback on the ice shelves of Antarctica
6. An additional simulation to complete experiment #3
7. A 2014-2100 simulation with RACMO2 at 11 km for Greenland following the SSP5-8.5 scenario.

All these three experiments were completed in 2019 and will be discussed below.

Additional, the following experiments were completed in 2019:

8. Two CESM2-driven historical RACMO2 runs for Greenland and Antarctica. These results are presented in the 2019 progress report. The results for the GrIS have been submitted to The Cryosphere (Noël et al, 2020a).
9. Sensitivity tests of snow melt production in Antarctica using an updated glaciated surface tile model embedded in RACMO2. The amount of snow melt on the ice shelves of Antarctica proved highly sensitive to parameterization choices. Multiple sensitivity experiments were therefore required to nail down the best working approach, which has been found now.
10. Shorter runs to update our operational SMB and climate data sets for the GrIS and AIS.

In 2019, 33.8 MSBU are used, which is slightly more than the granted budget of 23 + 10 MSBU.

On the following pages the completed experiments are discussed in detail using a geographical ordering.

RACMO2 simulations for Greenland

Updated reanalysis driven operational datasets (exp. #10)

We updated the simulation covering Greenland at 5.5 km to the end of August 2019, the date at which the ERA-Interim analysis was terminated. Furthermore, the statistically downscaled SMB estimates at 1 km resolution are extended to the last day of the RACMO2 simulation. These two updates extend the simulation carried out in 2018 – see the special report of 2018 and published in Noël et al, (2019).

A CESM2 driven historical simulation and projection for SSP5-8.5 (exp. #7 and #8)

We used the climate of the Community Earth System Model (CESM2; 111 km) to force RACMO2 for Greenland at 11 km resolution and simulated the historical (1950-2014) and projected (2015-2100) surface mass balance (SMB) of the Greenland ice sheet (GrIS) under a high-end warming scenario (SSP5-8.5; Fig. 1). The latter SMB product was statistically downscaled to 1 km spatial resolution following the method of Noël et al. (2016). This simulation is the core of three major publications: 1) CESM2-forced RACMO2.3p2 yields realistic present-day SMB and recent mass loss acceleration compared to various observations (Noël et al., 2020a); 2) the

Greenland ice sheet will enter a first phase of deglaciation (SMB < 0) in the mid-2050s (Noël et al., 2020b, under review); 3) Greenland firn will cross a tipping point in refreezing accelerating mass loss in the course of the 22nd century (Noël et al., 2020c, in prep.).

Based on the good agreement between native CESM2 and CESM2-forced RACMO2.3p2 SMB both in the historical (1950-2014) and future (2015-2100) periods, all currently available CESM2 simulations at 111 km resolution were statistically downscaled to 1 km including: industrial runs (1850-1949; 11 members), historical runs (1950-2014; 12 members), future projections including SSP1-2.6 to SSP5-8.5 (2015-2100; 22 members). This set of 45 downscaled products enable us to reconstruct 250 years of Greenland ice sheet SMB and components and will be used in forthcoming publications (Fig. 2).

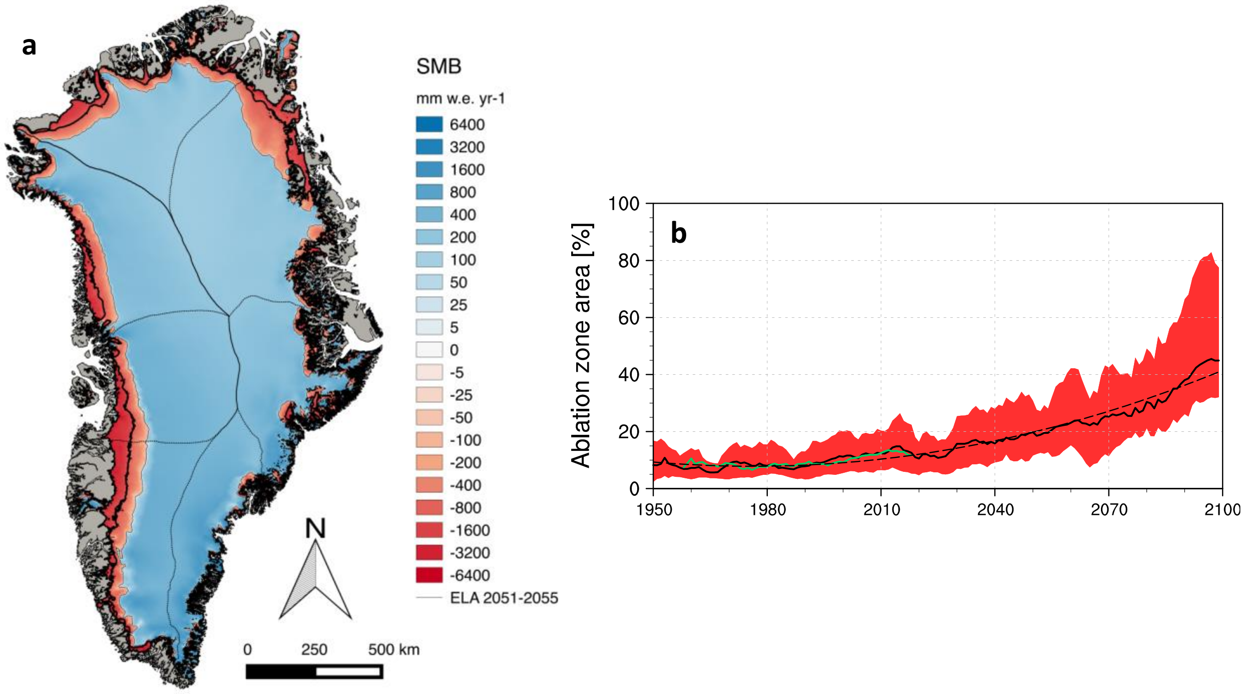

Figure 1: ***a*** *Surface mass balance (SMB) of the Greenland ice sheet averaged for 2050-2055. SMB is modelled by RACMO2.3p2 forced by CESM2 under a SSP5-8.5 scenario, and statistically downscaled to 1 km spatial resolution. Black lines show from thinnest to thickest the equilibrium line altitude (SMB = 0) of periods 1960-1990 when the ice sheet was in approximate mass balance, and 2050-2055 when integrated SMB of the ice sheet becomes negative.* ***b*** *Time series of the ice sheet ablation zone area, i.e. as a fraction of the total land ice area (%), for the period 1950-2100. Black line shows the ice sheet wide ablation zone area while the red band samples the different sectors shown in* ***a****. The green line shows the reanalysis-forced RACMO2.3p2 simulation for the period 1958-2018 (Noël et al., 2019). Dashed black line shows a quadratic fit.*

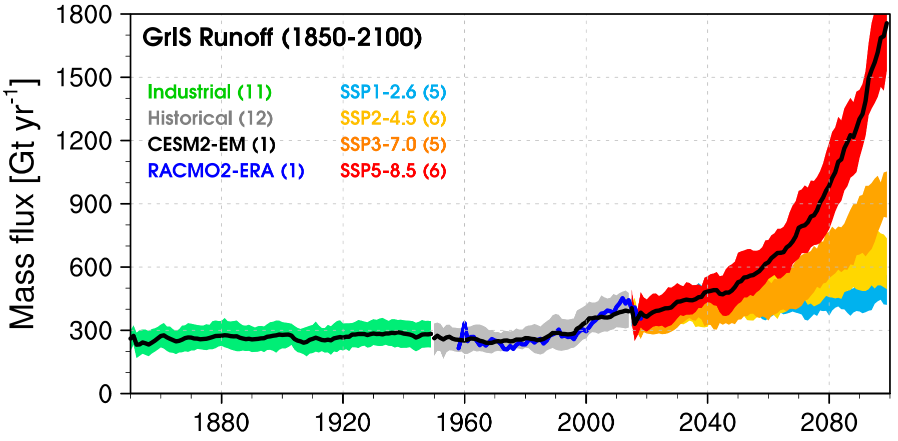

Figure 2: *Time series of Greenland ice sheet integrated runoff from various CESM2 simulations statistically downscaled to 1 km resolution for the period 1850-2100. In green the industrial period (1850-1949; 11 members), in grey the historical period (1950-2014; 12 members), in cyan, yellow, orange and red are scenarios SSP1-2.6 (2015-2100; 5 members), SSP2-4.5 (6), SSP3-7.0 (5) and SSP5-8.5 (6) respectively. The black line shows the CESM2 ensemble mean under a SSP5-8.5 scenario. The blue line shows the reanalysis-forced RACMO2.3p2 simulation for the period 1958-2018 (Noël et al., 2019).*

Improved representation of snow and ice albedo (exp. #3 and #6)

In 2019, the implementation and evaluation of a new narrowband snow and ice albedo scheme in RACMO2 was completed, which has resulted in a new version: RACMO2.3p3. The new albedo scheme uses the two-stream radiative transfer in snow model TARTES and the spectral-to-narrowband albedo module SNOWBAL, version 1.2. Compared to observations, the albedo product performs incredibly well, especially compared to the bias corrected MODIS MCD43A3 data (Fig. 3a). On average, the mean bias is only 0.010, while in the interior the bias is even smaller. Compared to the previous model version, RACMO2.3p2, the broadband albedo is considerably higher in the bare ice zone during the ablation season, as atmospheric conditions now alter the bare ice broadband as well.

Furthermore, with the addition of radiation penetration, snow is now allowed to heat internally, improving the subsurface temperature profile and extending melt to deeper layers (Fig. 3b). Analysis also shows that the surface mass balance is in good agreement with observations and that it only changes significantly around the ice margins and in the percolation zone. The radiative components of the surface energy balance are also in good agreement, although there is still room for improvements for the turbulent fluxes.

These results are described in two papers, one is in review (van Dalum et al., 2020a, in review), the other one is in preparation (van Dalum et al., 2020b, in prep).

Statistically downscaled products using RACMO2 data

Svalbard

We reconstructed 60 years of glacial mass balance in the Svalbard archipelago (1958-2019) using reanalysis-forced RACMO2.3 at 11 km, statistically downscaled to 500 m spatial resolution. This simulation shows that the low-elevation of Svalbard glaciers drives high mass loss variability, and is the core of a high-impact publication (Noël et al., 2020d, under review).

Iceland

We reconstructed 60 years of Iceland glacial mass balance using RACMO2.3 at 11 km (1958-2019), statistically downscaled to 500 m spatial resolution. This study is conducted in collaboration with the University of Iceland and will be the core of a forthcoming publication (Fig. 4).

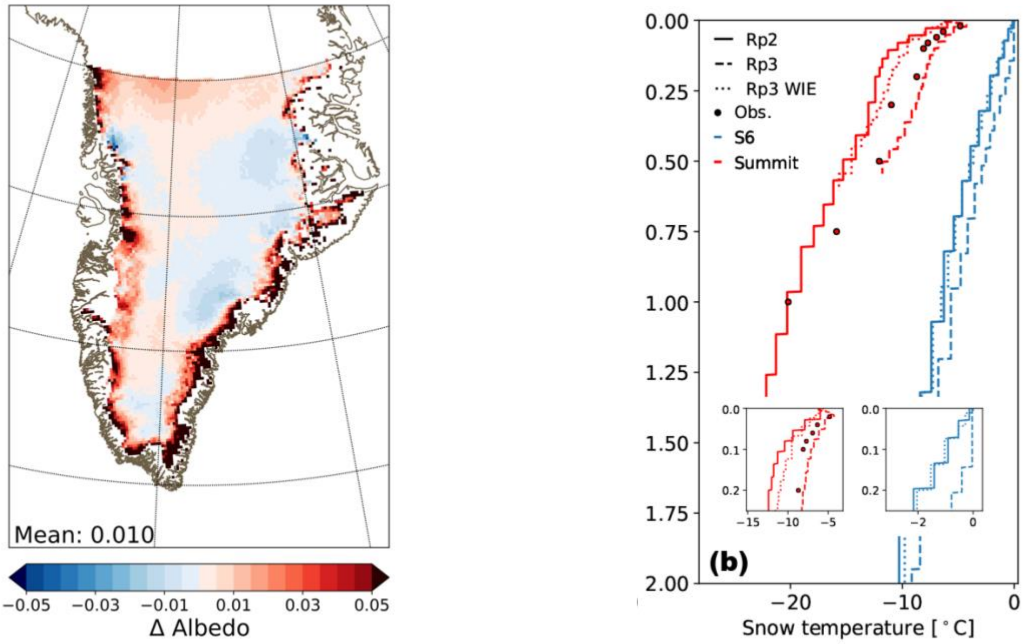

Figure 3: ***a*** *Average 16-days running mean clear-sky RACMO2.3p3 broadband albedo difference with MODIS MCD43A3 for 15:00 UTC (12:00 LT for most of Greenland) between 2006 and 2015.* ***b*** *Subsurface temperature profile for the 20 upper snow layers of RACMO2.3p2, RACMO2.3p3, RACMO2.3p3 without internal energy absorption (WIE) and observations for S6 and Summit for a summer day (10 July 2007) at 15:00 UTC. The insets show the results of the upper 25 cm in more detail. No observations are available for Summit on this winter day.*

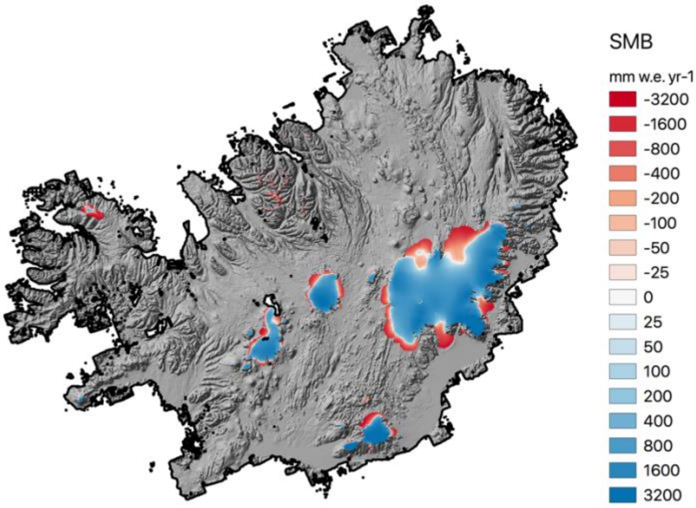

Figure 4: *Surface mass balance of Iceland ice caps as modelled by RACMO2.3, statistically downscaled to 500 m spatial resolution (1958-2018).*

RACMO2 simulations for Antarctica

Updated reanalysis driven operational datasets (exp. #10)

We updated the simulation covering Antarctica at 27 km to ten end of August 2019, the date at which the ERA-Interim analysis was terminated. This update extends the simulation carried out in 2018 – see the special report of 2018 and published in Van Wessem et al, (2018).

A CESM2 driven historic reconstruction (exp. #8)

Similarly as for Greenland, a 1950-2015 historic simulation of RACMO2, driven by CESM2 boundaries has been completed for the Antarctic domain. The results of this exercise are discussed in the 2019 special project progress report.

Dedicated sensitivity tests to determine the strength of the snowmelt-albedo feedback (exp. #5 and #9)

Surface melt is a crucial process for the stability of Antarctic ice shelves. In order to properly simulate surface melt, it is important to understand all related processes and feedbacks. One of these feedbacks is the snowmelt-albedo feedback (SMAF): when snow melts and refreezes, the surface albedo decreases. This leads to increased absorption of solar radiation by the surface, which in turn enhances surface melt. A single-point study using observations from Neumayer Station in East Antarctica showed that SMAF is capable of enhancing surface melt by a factor of 2.5 (Jakobs et al, 2019). This was achieved by using an albedo parameterisation that allows us to disable the effect of refrozen snow on surface albedo.

To put this value in context, we have performed two simulations with RACMO2, covering the Antarctic ice sheet and the surrounding ocean on a 27 km grid, for the period 1979-2018. One of these simulations served as a baseline run, the other simulation was performed without considering SMAF. Defining SMAF as the ratio of period-average seasonal melt rates between the two runs, shows significant spatial variability of SMAF (Fig. 5). The highest values are encountered on East Antarctic ice shelves, whereas SMAF is lowest in the Antarctic Peninsula and on the Ross and Filchner-Ronne ice shelves. Further analysis of the data showed that SMAF is most active in regions with average summer air temperature of 265 ± 2 K. In colder regions, surface melt amounts are generally low and melt is not sustained long enough for SMAF to significantly enhance it. In warmer regions, turbulent heat fluxes become more important for surface melt; this energy component is not affected by SMAF, and therefore SMAF is less active in these regions as well. On a sub-seasonal scale, precipitation also contributes to the importance of SMAF. As only snow is capable of raising the surface albedo, SMAF is stronger in seasons with a prolonged dry period. During such a period, the albedo remains low and SMAF stays active until a new snowfall event occurs and the feedback process is interrupted.

This study is now in review at Journal of Geophysical Research: Earth Surface (Jakobs et al, 2020). A preprint can be found at https://doi.org/10.1002/essoar.10503237.1.

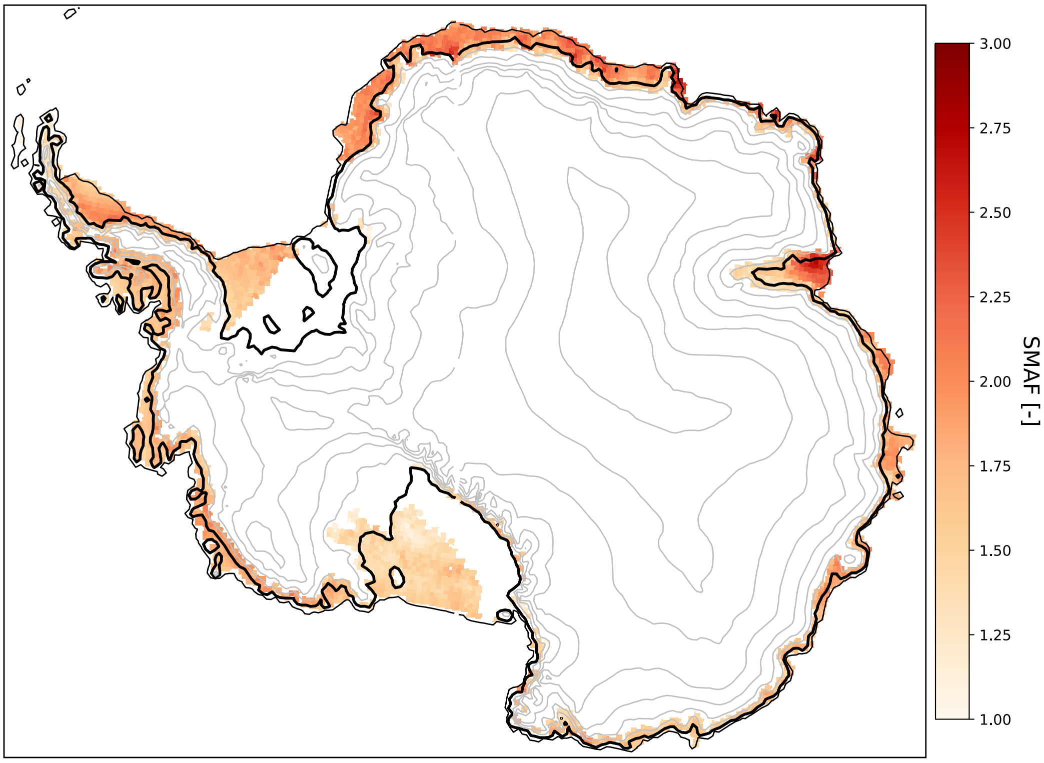

Figure 5: *Mean snowmelt-albedo feedback (SMAF) as modelled by RACMO2.*

Prior these published simulations, however, several discarded simulations were performed. In the exploring phase of this project, a slightly improved snow albedo model, similar to the model applied for the single point study, was tested. Due to reasons not clarified in 2019, this model version and all tests performed greatly overestimated snowmelt over the Antarctica Ice Shelves and were hence unsuitable for publication. Besides the undesired slowdown of a PhD project, these extensive inquiries to appropriate model settings took a significant fraction of initial computational resources of 2019.

List of publications/reports from the project with complete references

Preliminary list of publications based on computational efforts in 2019

Jakobs, C.L., C,H, Reijmer, C.H., M.R. van den Broeke, M.R., W.J. van de Berg, and J. M. van Wessem, 2020: Spatial variability of the snowmelt-albedo feedback in Antarctica, *under review*. Available at https://doi.org/10.1002/essoar.10503237.1

Noël, B., L. van Kampenhout, W.J. van de Berg, J.T.M. Lenaerts, B. Wouters, and M.R. van den Broeke, 2020a: Brief communication: CESM2 climate forcing (1950–2014) yields realistic Greenland ice sheet surface mass balance, *The Cryosphere*, **14**, 1425-1435, https://doi.org/10.5194/tc-14-1425-2020.

Noël, B., L. van Kampenhout, J.T.M. Lenaerts, W.J. van de Berg, and M.R. van den Broeke, 2020b: A 21st century warming threshold for sustained Greenland ice sheet mass loss, *under review*.

Noël, B., et al., 2020c: 22nd century collapse of firn refreezing capacity accelerates Greenland mass loss, *in preparation*.

Noël, B., C.L. Jakobs, W.J.J. van Pelt, S. Lhermitte, B. Wouters, J. Kohler, J.O. Hagen, B. Luks, C.H. Reijmer, W.J. van de Berg, and M.R. van den Broeke, 2020d: Low elevation of Svalbard glaciers drives high mass loss variability, *under review*.

Van Dalum, C.T., W.J. van de Berg, S. Lhermitte, and M.R. van den Broeke, 2020a: Evaluation of a new albedo scheme for the Greenland Ice Sheet in the regional climate model RACMO2, *under review.* Available at https://doi.org/10.5194/tc-2020-118

Van Dalum, C.T. et al, 2020b: Surface mass balance and energy budget of the Greenland Ice Sheet in RACMO2.3p3, *in preparation.*

Other cited papers (all based on or using data from preceding project years

Jakobs, C.L., C.H. Reijmer, P. Kuipers Munneke, G. König-Langlo, and M.R. van den Broeke, 2019: Quantifying the snowmelt-albedo feedback at Neumayer Station, East Antarctica, *The Cryosphere*, **13**, 1473-1485, doi: 10.5194/tc-13-1473-2019.

Noël, B.P.Y., W. J. van de Berg, H. Machguth, S. Lhermitte, I. Howat, X. Fettweis and M. R. van den Broeke**,** 2016: A daily, 1 km resolution data set of downscaled Greenland ice sheet surface mass balance (1958–2015), *The Cryosphere,* **10**, 2361-2377, doi:10.5194/tc-10-2361-2016.

Noel, B.P.Y., W.J. van de Berg, S. Lhermitte, M.R. van den Broeke, 2019: Rapid ablation zone expansion amplifies north Greenland mass loss, *Science Advances* **5** (9), doi: 10.1126/sciadv.aaw0123.

Van Wessem, J.M., W.J. van de Berg, B.P.Y. Noël, E. van Meijgaard, C. Amory, G. Birnbaum, C.L. Jakobs, K. Krüger, J.T.M. Lenaerts, S. Lhermitte, S.R.M. Ligtenberg, B. Medley, C.H. Reijmer, K. van Tright, L.D. Trusel, L.H. van Ulft, B. Wouters, J. Wuite and M.R. van den Broeke, 2018: Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 2: Antarctica (1979-2016), *The Cryosphere*, **12**, 1479-1498.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The plans for the second half of 2020 are discussed in the 2020 progress report. Plans for 2021 are described in the special project proposal for 2021.