SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Regional climate modelling of Greenland and Antarctica
Computer Project Account:	spnlberg
Start Year - End Year:	2020 - 2020
Principal Investigator(s)	Dr. Willem Jan van de Berg
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Other Researchers (Name/Affiliation):	Dr. Brice Noël, Dr. Melchior van Wessem, Dr. Carleen Reijmer, Dr. Peter Kuipers Munneke, Stan Jakobs, Christiaan van Dalum and Maurice van Tiggelen (UU/IMAU) Dr. Erik van Meijgaard (KNMI)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The objectives of our project in 2020 were threefold:
a) improving the model description of polar atmospheric processes and the atmosphere-ice sheet surface interaction;
b) provide accurate estimates of the contemporary climate and surface mass balance (SMB) of the two ice sheets and the larger glaciated regions;
c) provide projections of the future SMB of ice sheets.
For these objectives, the polar adapted version of the regional atmospheric climate model RACMO2 has been used.

Summary of problems encountered

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

During the fall of 2020, the access to data stored on ECFS was degraded, seriously hampering the workflow.

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 procedure goes smoothly, no comments on this.

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.)

At the ECMWF HPCF, we run our regional atmospheric climate model RACMO2, and a firn (multiyear snow) densification model IMAU-FDM. The various sub-projects are discussed one-by-one.

Objective a) Model development

Tuning and applying a spectral snow albedo model on the Antarctic Ice Sheet.

In the preceding years, we have developed a new version of the regional climate model RACMO2, version 2.3p3 (Rp3). This new version includes a new spectral snow albedo scheme and internal heating by sunlight. In 2019, we have applied and evaluated this updated version Rp3 to the Greenland Ice Sheet. In 2020, we applied Rp3 to the Antarctic ice sheet and evaluated the results by comparing with the previous RACMO2 version and in situ and remote sensing observations. Furthermore, we investigated the impact of internal heating and snow conditions to surface melt and subsurface snow temperatures on the Antarctic ice sheet.

The initial simulations, using the settings valid for Greenland, lead to biased result, therefore, several sensitivity experiments have been performed with Rp3. In this effort, one parameter at a time has been changed. Starting from the Greenland settings, the fresh snow grain size, fresh snow metamorphism, refreezing grain size and skin layer equilibration depth were altered. The latter depth is scaling depth that determines which fraction of the subsurface heating must be added to the skin layer, and which fraction must be added to the snow.

After tuning, Rp3 compares well with in situ and remote sensing observations of surface mass balance (SMB) and surface energy balance, snowmelt, temperature, albedo and snow grain size. Furthermore, the addition of subsurface heating significantly improves the subsurface snow temperature profile. This study also shows that the near-surface snow temperature is especially sensitive to the prescribed fresh snow grain size and dry snow metamorphism and that the these two are also important for snowmelt around the margins of the Antarctic ice sheet. Moreover, incorrectly modeling the aforementioned processes can lead to an order of magnitude overestimation of snowmelt (Fig. 1), locally leading to runoff and a reduced SMB.

Retuning the firn densification model IMAU-FDM

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 (Ligtenberg et al, 2018). By using IMAU-FDM, a more accurate estimate of melt water retention and refreezing is obtained. IMAU-FDM is run per model grid box as single core task

In 2020, the descriptions of densification rate, surface density parameterization and thermal conductivity within IMAU-FDM have been updated to improve the performance of IMAU-FDM. For this aim, multiple historic runs of several point locations at the Greenland ice sheet for which relevant firn observations are available, have been conducted. The update leads to an improved model performance, as demonstrated in the Figure 2. In this Figure, the modelled firn air content from the old and the new model is compared against observations.

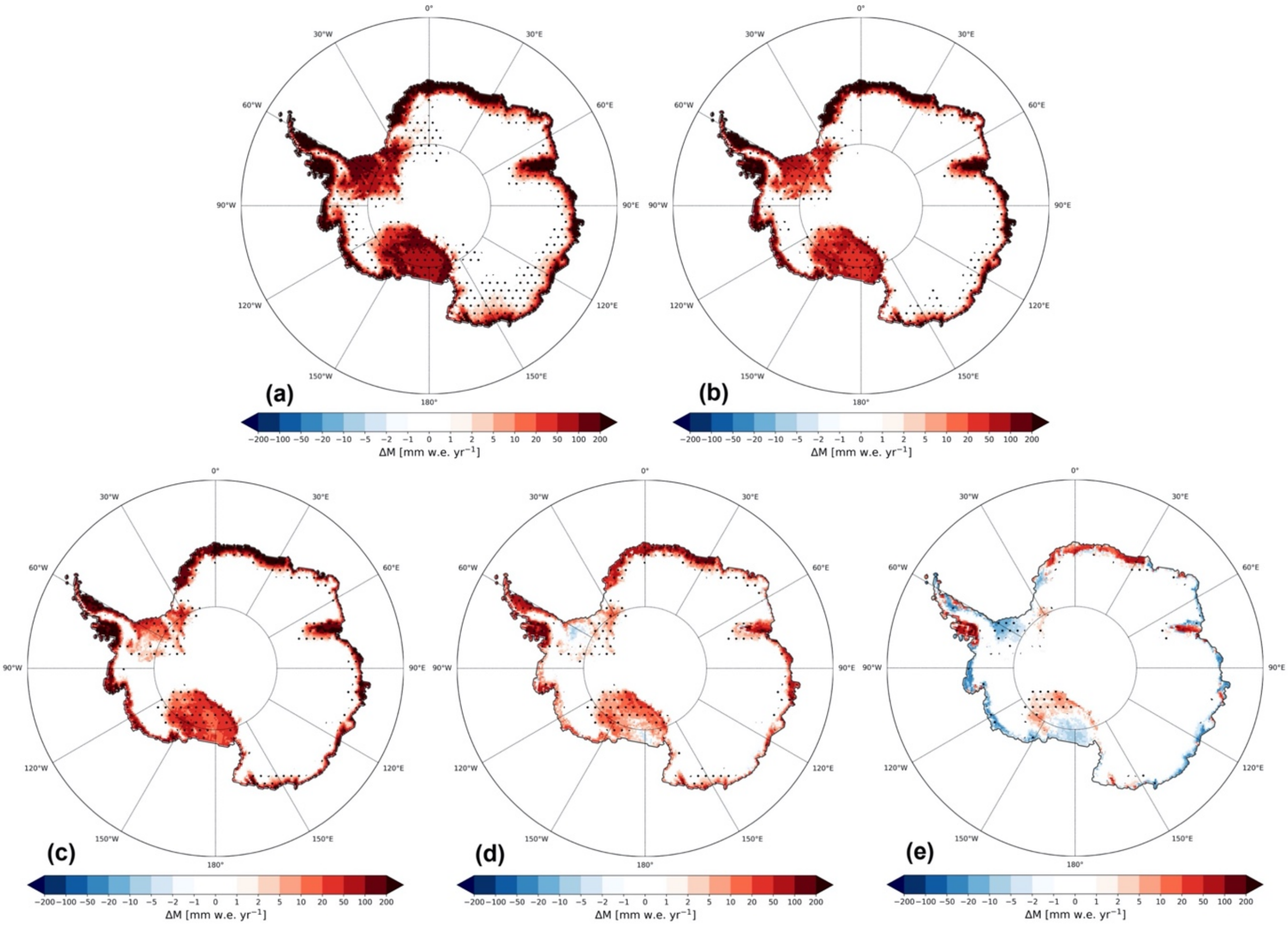

***Figure 1:** Mean yearly accumulated snowmelt difference of RACMO2.3p3 with the previous RACMO2 version for **(a)** the Greenland settings, **(b)** smaller fresh snow grains, **(c)** slower fresh snow metamorphism, **(d)** smaller refreezing grain size and **(e)** larger skin layer equilibration depth leading to reduced subsurface heating.*

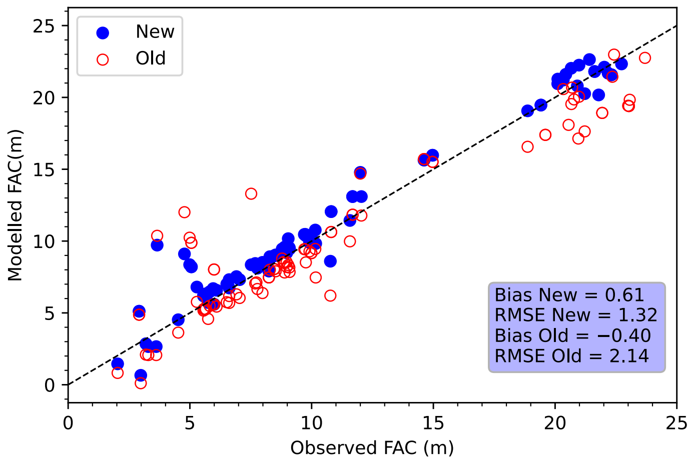

***Figure 2:** Modelled versus observed firn air content in meters, with the results from IMAU-FDM using the new model settings displayed in blue and the results with the old model settings shown in red.*

Objective 2: provide benchmark simulations of the contemporary climate and surface mass balance (SMB) of the two ice sheets and the larger glaciated regions

Greenland, Svalbard and Iceland

We processed a new benchmark data set of the Greenland ice sheet (GrIS) SMB using RACMO2.3p2 (5.5 km) forced by the latest ERA5 climate reanalysis (1990-2021), further statistically downscaled to 1 km (see black line in Fig. 3). This new data set is an extension of our work published in Noël et al. (2019, Science Advances), and will be used as reference in our forthcoming papers. We also completed our work on the recent mass change of Svalbard glaciers at 500 m spatial resolution, published in Noël et al. (2020a, Natcomms) (see Fig. 4 left). Similarly, the SMB data is downscaled for the Icelandic glaciers (Fig 4. right). These simulations are updated with ERA5T every two to three months.

Antarctica

We aimed to increase the resolution of our operational products for Antarctica from 27 km to 11 km. This resolution has been chosen as an optimal balance between resolution and computational costs. In order to minimize domain settings effects, the 11 km simulations have been run with a near equivalent model domain. Nonetheless, analysis showed that on this higher resolution, a significant shift in precipitation patterns occurs in the model. Figure 5 shows the modelled SMB, which is largely determined by precipitation, for both resolutions and the SMB difference Coastal precipitation decreases somewhat, but this change is within uncertainty ranges. More importantly, inland

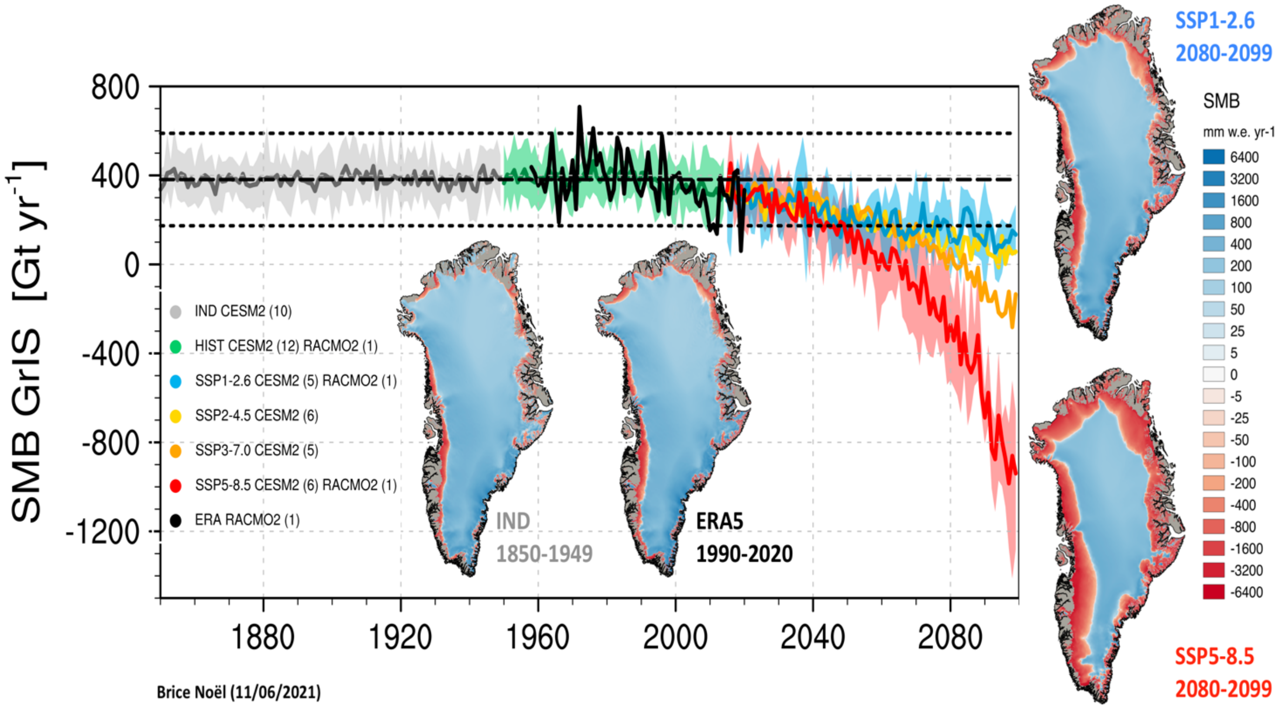

Figure 3: *Time series of Greenland ice sheet (GrIS) integrated surface mass balance (SMB) for the period 1850-2100. RACMO2.3p2 at 1 km forced by ERA40 (1958-1978), ERA-Interim (1979-1989) and ERA5 (1990-2020) is shown in black. Colored lines represent ensemble means of multiple CESM2 runs statistically 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. Colored bands show the range of individual members. Inset maps show SMB averaged for the industrial period (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).*

precipitation increases significantly (by 200 Gt, not shown) and likely exceeds ranges given by observations. For example, the current 27 km product compares well with the observed ice discharge rates, and this amount of higher precipitation amounts will worsen the comparison. This new wet bias can likely be mitigated by retuning precipitation formation time scales again, as was done before for the 27 km product. However, we decided to postpone this for now and readopt 27 km as the default resolution for operational Antarctic simulations. This 27 km resolution operational simulation has been updates using ERA5T twice a year.

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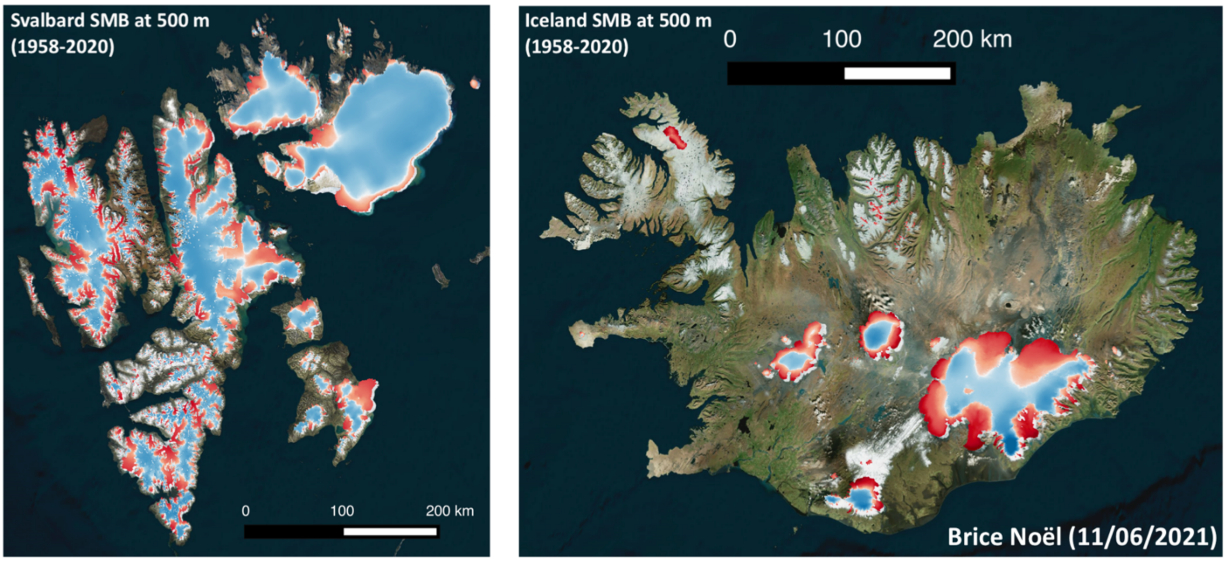

Figure 4: *SMB maps of Svalbard (left) and Iceland glaciers (right) at 500 m spatial resolution averaged for 1958-2020. These data are statistically downscaled from RACMO2.3 at 11 km onto a 500 m resolution grid. Accumulation zones (SMB > 0) are shown in blue, while ablation zones (SMB < 0) are represented in red.*

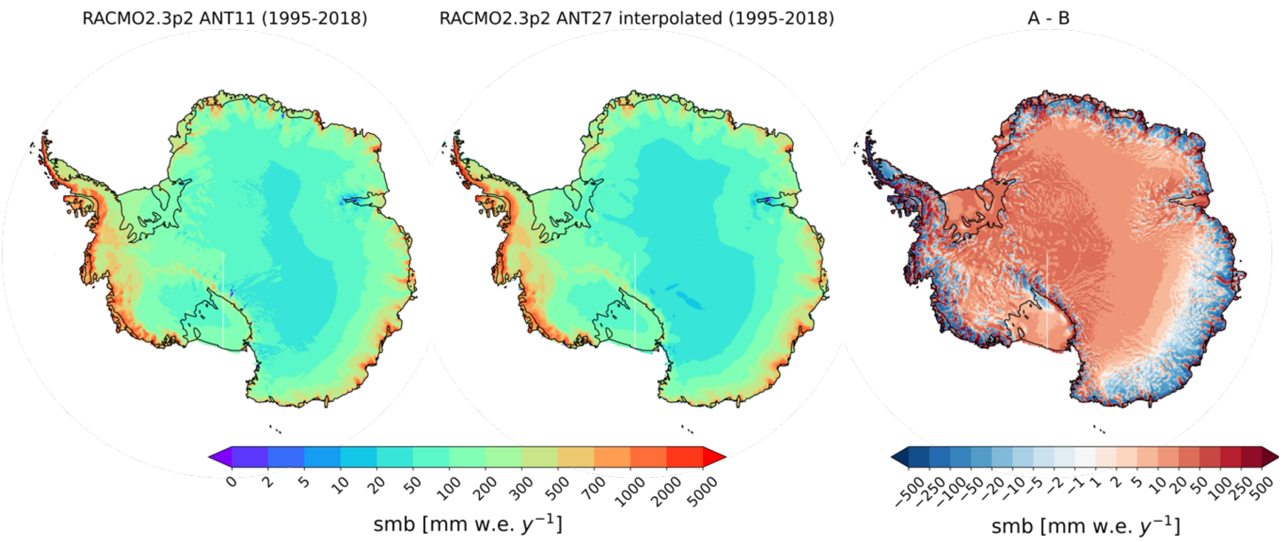

Figure 5: *RACMO2.3p2 ANT11 (left) and RACMO2.3p2 ANT27 interpolated on the 11 km grid (middle) SMB and their difference (right).*

Objective 3: provide projections of the future SMB of ice sheets.

Greenland Ice Sheet

In 2019, we completed a CESM2 driven RACMO2 simulations for historic past (1950-2010) and pathway SSP RCP5-8.5 (red line in Fig. 3), which was analyzed in 2020 and a manuscript was submitted subsequently. In 2021, we completed a CESM2 driven RACMO2 simulation for the pathway SSP RCP1-2.6 (blue line in Fig. 3), which is discussed in the midterm report for 2021.

Antarctic Ice Sheet

For the Antarctic Ice Sheet, the ECMWF HPCF have been used to create an updated RACMO2.3p2 future projection up to 2100 for the RCP pathway SSP5-8.5, using boundary data from CESM2. The RACMO2 simulations have been carried out on a horizontal resolution of 27 km. A simulation for the pathway SSP1-2.6 again using CESM2 boundaries was planned for 2021. The simulation for SSP5-8.4 has been completed and analyzed in 2020, and the results looked correct.

However, when the first results for the SSP1-2.6 simulation were analyzed in early 2021, deviations in the modelled melt were observed. After thorough analysis, it was found out that for the CESM2-driven simulations of 2019 and 2020, an incorrect model version was used. Given the manageable costs of these simulations, we decided to rerun the historical period (1950-2010) and SSP5-8.5 (2010-2100) simulations which were completed in 2019 and 2020, respectively.

The new simulations have been completed and they are presented in the SPNLBERG progress report of 2021.

List of publications/ from the project with complete references

Listed below are publications appeared in 2020 and 2021, or in draft, based on model results derived with SPNLBERG resources. All such publications from SPNLBERG researchers are listed and selected only the highlight papers from researchers outside our research group.

1. Felikson, D., G. Catania, T. C. Bartholomaus, M. Morlighem and B. P. Y. Noël. Steep glacier bed knickpoints mitigate inland thinning in Greenland, Geophysical Research Letters, e2020GL090112, 2020. doi: 10.1029/2020GL090112.
2. Jakobs, C.L., C.H. Reijmer, M.R. van den Broeke, W.J. van de Berg, and J.M. van Wessem, 2021. Spatial variability of the snowmelt–albedo feedback in Antarctica. *J. Geophys. Res.: Earth Surface*, 125. doi:10.1029/2020JF005696.
3. Jakobs, C.L., C.H. Reijmer, C.J.P.P. Smeets, L.D. Trusel, W.J. van de Berg, M.R. van den Broeke, J. M. van Wessem, 2020. A benchmark dataset of in situ Antarctic surface melt rates and energy balance, *J. Glaciol.*, 66(256), 291-302, doi:10.1017/jog.2020.6.
4. King, M. D., I. M. Howat, S. G. Candela, M. J. Noh, S. Jeong, B. Noël, M. R. van den Broeke, B. Wouters and A. Negrete. Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat, Nature Communications Earth & Environment, 1(1) : 1-7, 2020. doi : 10.1038/s43247-020-0001-2.
5. Laffin, M. K., Zender, C. S., Singh, S., Van Wessem, J. M., Smeets, C. J. P. P., and Reijmer, C. H. (2021). Climatology and Evolution of the Antarctic Peninsula Föhn Wind-Induced Melt Regime From 1979–2018. *Journal of Geophysical Research: Atmospheres*, *126*(4), 1–19. doi:10.1029/2020JD033682. issn:21698996.
6. Lai, C. Y., Kingslake, J., Wearing, M. G., Chen, P. H. C., Gentine, P., Li, H., Spergel, J. J., and van Wessem, J. M. (2020). Vulnerability of Antarctica's ice shelves to meltwater-driven fracture. *Nature*, *584*(7822), 574–578. doi:10.1038/s41586-020-2627-8. issn:14764687.
7. 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.

8. Mankoff, K. D., B. Noël, X. Fettweis, A. P. Ahlstrøm, W. Colgan, K. Kondo, K. Langley, S. Sugiyama and D. van As and R. S. Fausto. Greenland liquid water discharge from 1958 through 2019, Earth System Science Data, 12(4): 2811-2841, 2020. doi: 10.5194/essd-12-2811-2020.
9. Mankoff, K. D., X. Fettweis, P. L. Langen, M. Stendel, K. K. Kjledsen, N. B. Karlsson, B. Noël, M. R. van den Broeke, W. Colgan, S. B. Simonsen, J. E. Box, A. Solgaard, A. P. Ahlstrøm, S. Bech Andersen and R. S. Fausto. Greenland ice sheet mass balance from 1840 through next week, Earth System Science Data Discussion, 7(1): eaba728, 2021. doi: 10.5194/essd-2021-131.
10. Mottram, R., Hansen, N., Kittel, C., van Wessem, M., Agosta, C., Amory, C., Boberg, F., van de Berg, W. J., Fettweis, X., Gossart, A., van Lipzig, N., van Meijgaard, E., Orr, A., Phillips, T., Webster, S., Simonsen, S., and Souverijns, N. (2020). What is the Surface Mass Balance of Antarctica? An Intercomparison of Regional Climate Model Estimates. *The Cryosphere Discussions*, (January), 1–42. doi:10.5194/tc-2019-333. issn:1994-0416.
11. Mouginot, J., E. Rignot, A. A. Bjørk, M. R. van den Broeke, R. Millan, M. Morlighem, B. Noël, B. Scheuchl and M. Wood. Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018, PNAS, 116(19): 9239-9244, 2019. doi: 10.1073/pnas.1904242116.
12. Noël B., W. J. van de Berg, S. Lhermitte, and M. R. van den Broeke. Rapid ablation zone expansion amplifies north Greenland mass loss, Science Advances, 5: eaaw0123, 2019. doi: 10.1126/sciadv.aaw0123.
13. Noël B., C. L. Jakobs, W. J. J. van Pelt, S. Lhermitte, B. Wouters, J. Kolher, J. O. Hagen, B. Luks, C. H. Reijmer, W. J. van de Berg and M. R. van den Broeke. Low elevation of Svalbard glaciers drives high mass loss variability, Nature Communications, 11(4597): 1-8, 2020. doi: 10.1038/s41467-020-18356-1.
14. Noël B., L. van Kampenhout, W. J. van de Berg, J. T. M. Lenaerts, B. Wouters and M. R. van den Broeke. Brief communication: CESM2 climate forcing (1950-2014) yields realistic Greenland ice sheet surface mass balance, The Cryosphere, 14(4): 1425-1435, 2020. doi: 10.5194/tc-14-1425-2020.
15. Noël B., L. van Kampenhout, J. T. M. Lenaerts, W. J. van de Berg and M. R. van den Broeke. A 21st century warming threshold for irreversible Greenland ice sheet mass loss, Geophysical Research Letters, 48(5): e2020GL090471, 2021. doi: 10.1029/2020GL90471.
16. Noël B., G. Aðalgeirsdóttir, F. Pálsson, B. Wouters, S. Lhermitte, J. Haacker and M. R. van den Broeke. North Atlantic cooling slows down mass loss of Iceland glaciers. Submitted.
17. Spergel, J., Kingslake, J., Creyts, T., Van Wessem, M., & Fricker, H. (2021). Surface meltwater drainage and ponding on Amery Ice Shelf, East Antarctica, 1973–2019. *Journal of Glaciology,* 1-14. doi:10.1017/jog.2021.46.
18. The IMBIE Team. Mass balance of the Greenland Ice Sheet from 1992 to 2018, Nature, 2019. doi: 10.1038/s41586-019-1855-2.
19. Van Dalum, C. T., Van de Berg, W. J., Lhermitte, S., and Van den Broeke, M. R., Evaluation of a new snow albedo scheme for the Greenland ice sheet in the Regional Atmospheric Climate Model (RACMO2), The Cryosphere, 14, 3645-3662, https://doi.org/10.5194/tc-14-3645-2020, 2020.
20. Van Dalum, C. T., Van de Berg, W. J., and Van den Broeke, M. R., Impact of updated radiative transfer scheme in RACMO2.3p3 on the surface mass and energy budget of the Greenland ice sheet, The Cryosphere, 15, 1823-1844, https://doi.org/10.5194/tc-15-1823-2021, 2021.
21. Van Dalum, C. T., Van de Berg, W. J., and Van den Broeke, M. R., Impact of radiation penetration on Antarctic surface melt and subsurface snow temperatures, in preparation, 2021.
22. Van de Berg, W. J., E. van Meijgaard, L. H. van Ulft, The added value of resolution in estimating the surface mass balance in southern Greenland, The Cryosphere, 14, 1809-1827, https://doi.org/10.5194/tc-14-1809-2020, 2020.
23. Van Wessem, J. M., Steger, C. R., Wever, N., and Van Den Broeke, M. R. (2021). An exploratory modelling study of perennial firn aquifers in the Antarctic Peninsula for the period 1979-2016. *Cryosphere*, *15*(2), 695–714. doi:10.5194/tc-15-695-2021. issn:19940424.
24. Wood, M., E. Rignot, L. An, A. Bjørk, M. van den Broeke, C. Cai, I. Fenty, E. Kane, D. Menemenlis, R. Millan, M. Morlighem, J. Mouginot, B. Noël, B. Scheuchl, I. Velicogna, J. Willis and H. Zhang. Ocean forcing drives glacier retreat in Greenland, Science Advances, 7(1): eaba728, 2021. doi: 10.1126/sciadv.aba7282.

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.)

Please read the SPNLBERG midterm report for our plans for the remainder of 2021 and the special project application for 2022 for our plans for next year.