# 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 |
| **Computer Project Account:** | spnlberg |
| **Start Year - End Year :** | 2018 - 2018 |
| **Principal Investigator(s)** | Dr. W. J. van de Berg |
| **Affiliation/Address:** | Institute for Marine and Atmospheric Research Utrecht (IMAU)<br>Utrecht University,<br>Princetonplein 5,<br>3584 CC Utrecht,<br>The Netherlands |
| **Other Researchers (Name/Affiliation):** | Dr. Brice Noël, Dr. Melchior van Wessem, Dr. Carleen Tijm-Reijmer, Jasper Wiesenekker, Stan Jakobs, Christiaan van Dalum and Dr. Stefan Ligtenberg.<br>IMAU, Utrecht University |

The following should cover the entire project duration.

## Summary of project objectives

(10 lines max)

This project aims to facilitate the research at the Institute for Marine Research Utrecht (IMAU), Utrecht University, on the climate and surface mass balance of the Greenland and Antarctic Ice Sheets and the larger glaciated regions on Earth. Primary numerical tool is the regional polar adapted climate model RACMO2.3p2, complemented by statistical downscaling and the firn[*] densification models IMAU-FDM and SNOWPACK. With these models, we investigate the driving atmospheric and surface processes that influence the mass balance of ice sheets in order to deliver reliable projections of surface mass loss and snow melt enhancement for different emission scenarios.

## Summary of problems encountered

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

The planned GCM driven simulations by the regional climate model RACMO2.3p2 for 2018 were postponed by the strongly delayed release of CESM2, the intended GCM to use. Once CESM2 was released in July 2018, it appeared to be more cumbersome to implement model adjustments so that RACMO2 could run on a 365-day calendar. This technicality has been solved in 2018 but the longer CESM2-driven simulations were postponed to 2019.

## 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 2018

In the project proposal, the following runs were proposed:

1) A present-day (1979-2017) ERA-5 driven run for Greenland on 5.5 km resolution. As ERA-5 was not timely available, in 2018 we continued simulation of the ERA-40 driven, 5.5 km resolution run for Greenland (1958-1978) and extended this run to the end of 2018 by using ERA-Interim. This simulation is discussed in detail below. The computational costs of this simulation were about 6.5 MSBU.
2) A present-day (1979-2017) ERA-5 driven run for Antartica on 18 km resolution. This run has been cancelled because of the delayed release of ERA-5.
3) A future climate (1980-2100) run for the Antarctic Peninsula driven by CESM2 data. This simulation has been postponed as it was intended to be done after similar simulations for Greenland and the whole Antarctica. These latter simulations were postponed to 2019 due to major delays in the release of CESM2 and unexpected technical problems in the one-way coupling of RACMO2.3p2 with CESM2, briefly discussed above.

---

[*] Firn is snow older than one year.

4) Test runs facilitating the implementation of a narrowband albedo model into RACMO2.3p2. In 2018, some short test runs were carried out, but as most relevant tests were carried out in 2019, an update is given in the 2019 progress report of the SPNLBERG project.

Additionally, the following simulations have been carried out:

1) It was initially planned that the firn densification simulations, which were not included in the SPNLBERG project, would be carried out using the general KNMI budget. On request of the KNMI these simulations were also accounted under the SPNLBERG project. The results of these simulations are discussed below. The combined costs of the various firn densification simulations are in total about 3.1 MSBU.
2) In 2018, the RACMO2.3p2 high-resolution run of Svalbard has been completed and the subsequent statistical downscaling has been applied. The run completion and statistical downscaling needed about 1.3 MSBU in 2018. The results of the simulation and downscaling are already discussed in the SPNLBERG final report of 2017.
3) Several model sensitivity runs on a small model domain covering South Greenland have been carried out, costing in total about 0.7 MSBU. These runs are discussed below.

Still, because of the delays of the major simulations, only 11.8 MSBU of the requested 30 MSBU has been used in 2018. As this became apparent at the end of 2018 that not all resources would be used, 10 MSBU has been handed back to the ECMWF by 3 December 2018.

## RACMO2 simulations for Greenland

In 2018 we completed a 5.5-kilometre resolution ERA-40 (1958-1978) and ERA-interim (1979-2018) driven RACMO2.3p2 simulation covering Greenland. After completion of the simulation, the daily surface mass balance (SMB) is statistically downscaled to 1 km following the procedure described by Noël et al (2016).

Evaluation of the modelled and statistically downscaled shows that both the modelled and statistically downscaled SMB agrees better with observations than the equivalent simulation at 11 km resolution (Fig 1). For many observations, both the 11 km and 5.5 km run give good SMB estimates. However, for a substantial fraction of the observations, the ablation is underestimated by RACMO2. This underestimation has been reduced in the 5.5 km run. As a result, the statistically downscaled SMB from 5.5 km data correlates better with observations than that of the equivalent product at 11 km.

Using this new model simulation, the influence of clouds on the observed expansion of the GrIS ablation zone has been analysed. In particular in the north-western sector of the GrIS, spanning from 72 °N to 27 °W, mass loss increase was more pronounced and the ablation area expanded faster than in other regions of the GrIS. Noël et al. (accepted) demonstrate that increased cloudiness, induced by changes in the large-scale summertime Arctic circulation, have a critical role in the regionally enhanced increase in ablation.

Besides this publication, it is expected that the data from this simulation will be used in numerous publications by other researchers; in 2018 and so far in 2019, data has been shared >200 times with ~100 researchers outside IMAU (13 countries). Finally, results will be incorporated in the upcoming IPCC special report on The Ocean and Cryosphere in a Changing Climate (SROCC).

## Climate projections with RACMO2 for Antarctica and Greenland

In order to provide accurate projections of the Antarctic climate in the 21st and 22nd century, RACMO2.3p2 is one-way coupled to the Earth System Model CESM2 (http://www.cesm.ucar.edu/models/cesm2/). Initial short simulations for Antarctica gave very promising results, but longer simulations were delayed to 2019 because of the time required to adapt RACMO2.3p2 to a 365-day calendar. The historic simulations for Greenland and Antarctica have been completed in the first months of 2019 and are discussed in the progress report of 2019.

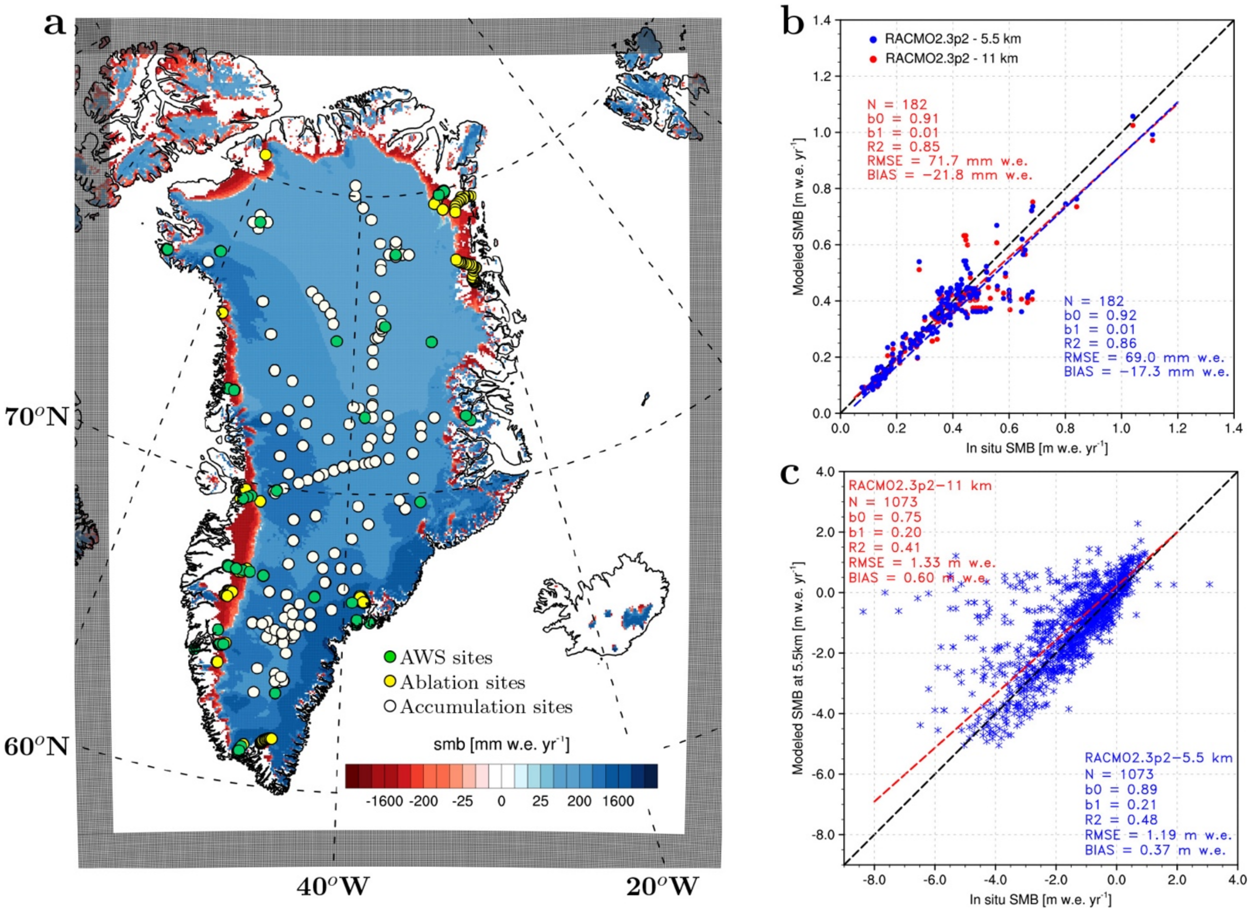

***Figure 1: (a)** Annual mean surface mass balance (smb) as modeled by RACMO2.3p2 at 5.5 km horizontal resolution averaged for the period 1958-2017. Black dots delineate the relaxation zone (24 grid cells) where the model is forced by ERA re-analyses. Green dots locate 23 AWS used for further model evaluation (not discussed here). Comparison of modeled 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 previous 11 km (red dots) with the new 5.5 km (blue dots) versions 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 11 km (red) and 5.5 km (blue) simulations. Figure 1c also displays regression line (red dashed line) and associated statistics for the ablation zone. For clarity, modelled ablation from the 11 km version is left out in Fig. 1c.*

## RACMO2 sensitivity simulations over South Greenland

In 2016, RACMO2.3p1 simulations were conducted over South Greenland on resolutions ranging from 60 to 2.2 km. In order to compare the changes in modelled SMB with the uncertainties induced by choices made while initializing the simulations or parametric uncertainties, several sensitivity simulations have been carried out, covering 2006 to 2014 and driven by ECMWF operational analyses. The deviation in modelled SMB of the six most relevant simulations are shown in Figure 2, leaving out 2006 as spin-up. Please note that the SMB ranges from about -3 m w.e. $a^{-1}$ in the western ablation zone, about 0.4 m w.e. $a^{-1}$ on the central part of the ice sheet and varies from -1 to +3 m w.e. $a^{-1}$ along the eastern margin (see Figure 1).

Figure 2a shows that a precise initialization of the firn column is essential as this simulation is initialized with a thick instead of thin firn layer. Although the impact on the mean SMB is largest in the lower ablation zone, this impact is short lived. After a few summers the initial and anomalous firn layer has been melted away and the modelled SMB becomes similar to the simulation started with very little snow over ice. However, along the equilibrium line – the thick black lines in Figure 2 – the impact of the chosen firn column initialization is still pronounced after almost a decade. Figure 2b and 2c show that a correct representation of the snow and ice albedo is essential as modest changes in these albedos lead to notable differences in SMB. Figures 2d-f show that the uncertainty in SMB induced by turbulent fluxes is of lesser importance except for the lower ablation zone. Figure 2d shows that the SMB is virtually insensitive to the roughness length for momentum ($z_{0m}$), the estimated roughness of the terrain, which is an effect of default parameterization of the roughness length for heat and moisture over snow and ice in RACMO2.3p1. If this parameterization is switched off (Fig. 2e and 2f) melt and subsequently runoff and SMB become more sensitive to the chosen $z_{0m}$. A publication on these results is in preparation.

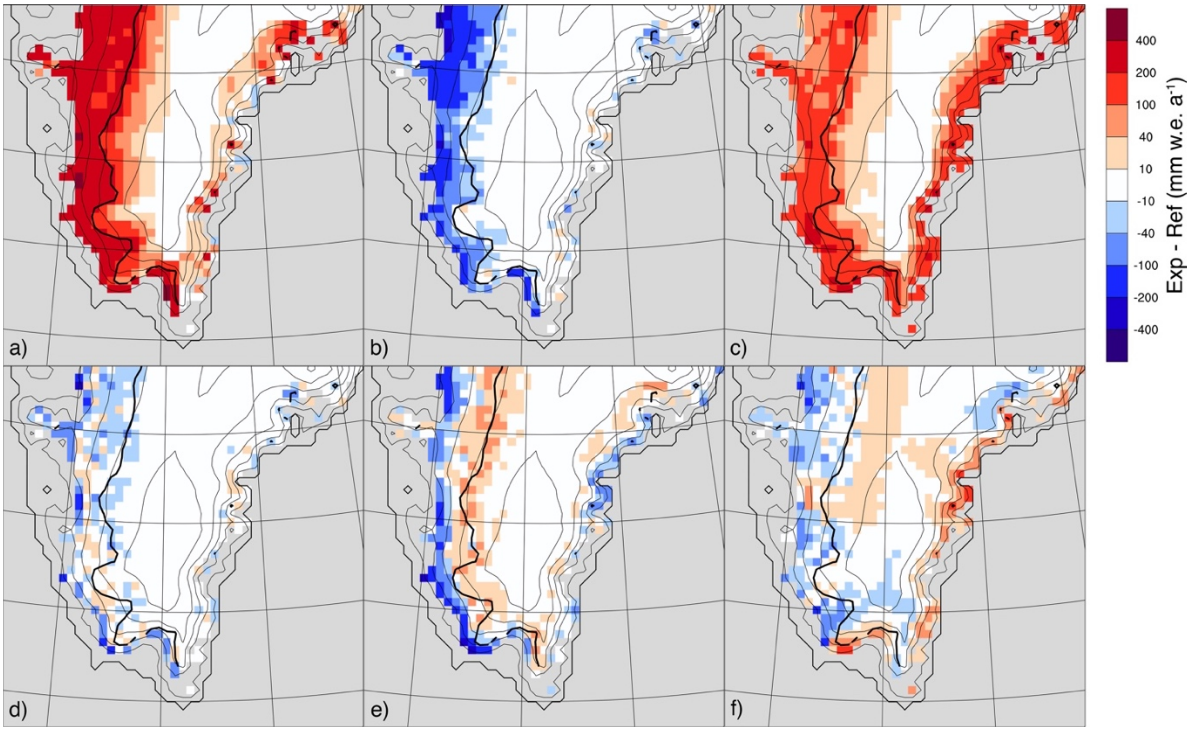

***Figure 2:*** *Differences in the modelled mean annual surface mass balance from 6 sensitivity simulation compared to the reference experiment, all covering the years 2007 to 2014.* ***a)*** *Initializing RACMO2.3p1 not with a thin, 50 cm thick snow layer on top of an ice column but with a 10 m thick firn layer on top of an ice column.* ***b)*** *Reducing the prescribed albedo of glacial ice from 0.42 to 0.38.* ***c)*** *Halving the impurity content of snow.* ***d)*** *increasing the roughness length for momentum ($z_{0m}$) of glacial ice from 0.5 to 10 cm* ***e) and f)*** *Assuming that the roughness lengths for heat and moisture are equal to $z_{0m}$, using a $z_{0m}$ of* ***e)*** *0.1 and* ***f)*** *0.05 mm over snow covered surfaces. The black line denotes the equilibrium line (SMB=0) in the references simulation; southwest Greenland has a large ablation zone, ablation zones in southeast Greenland are very confined due to the much higher snowfall rates.*

## Firn densification runs for Greenland and Antarctica

Following on the completion of ERA-driven RACMO2.3p2 simulations for Greenland (11 and 5.5 km resolution), Antarctica (27 km resolution) and the Antarctic Peninsula (5.5 km) in 2017, detailed estimations of the evolution of the firn column were carried out in 2018. In firn columns, which are up to 100 m thick, low density fresh snow gradually metamorphoses into glacial ice due to compression and meltwater refreezing. Firn processes are well understood in dry snow areas and in the ablation zone, where all snow and firn disappears in summer. However, firn processes are less well understood in the percolation zone where the retention and refreezing of melt water is the dominant process for the evolution of the firn column.

These uncertainties are visualized in Figure 3. Here, modelled density profiles of two different firn densification models, IMAU-FDM and SNOWPACK, are compared with firn cores collected on the Larsen-C ice shelf, Antarctic Peninsula, Antarctica. Please note that the vertical scale varies for all sub-plots. In some cases, sites J2_08 or LAR1, both models resemble well the observed densities. For other cores, WI0 and WI70, both models are well off albeit by different margins, here annual melt is underestimated by RACMO2.3p2. For all other sites, the two modelled density differ as much from each other as from the observed profile, highlighting the remaining uncertainties in modelling the firn evolution in regions of considerable melt.

Despite the remaining uncertainties, firn models can be used to estimate the influence of firn processes on the elevation of the Antarctic and Greenland Ice Sheets. Elevation changes, which is observable with satellite altimetry, can be due to three processes: changes in the ice flow, surface mass balance and firn column. Changes in the ice flow relate to changes in ice discharge, hence changes in ice flow and surface mass balance relate to mass changes of the ice sheet. Changes in the firn column, hence a gain or loss of air content, leads to elevation changes without mass changes. Figure 4 shows the evolution of dH/dt for the Greenland Ice Sheet due to changes in the SMB and firn air content. If the SMB and firn evolution is well estimated, the remaining fraction of the dH/dt signal as observed by altimetry should resemble the dynamically thinning/thickening due to enhanced/reduced ice discharge of the outlet glaciers of the Greenland Ice sheet. These results are partially an update of Ligteberg et al, 2018, and will not be separately published. Nevertheless, this and preceding data is shared; we receive about 20 data request each year.

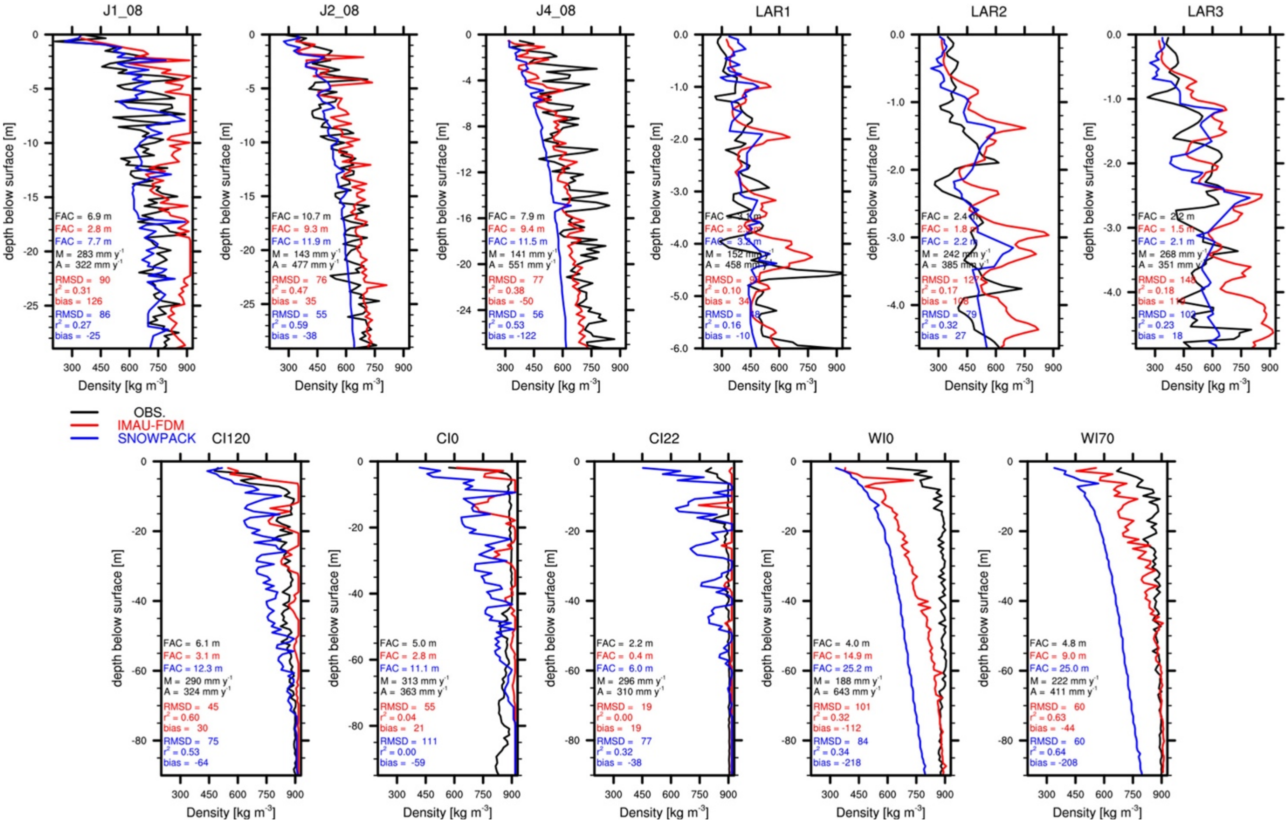

***Figure 3:*** *Evaluation of modelled density profiles, using the models IMAU-FDM and SNOWPACK, with observed profiles for 11 sites on the Larsen-C Ice Shelf, Antarctica. FAC denotes the firn air content integrated over the length of the firn core. Both IMAU-FDM and SNOWPACK are driven by mass fluxes from RACMO2.3p2 (van Wessem et al, 2018); the mean annual prescribed melt (M) and accumulation (A) rates are included in the graphs.*

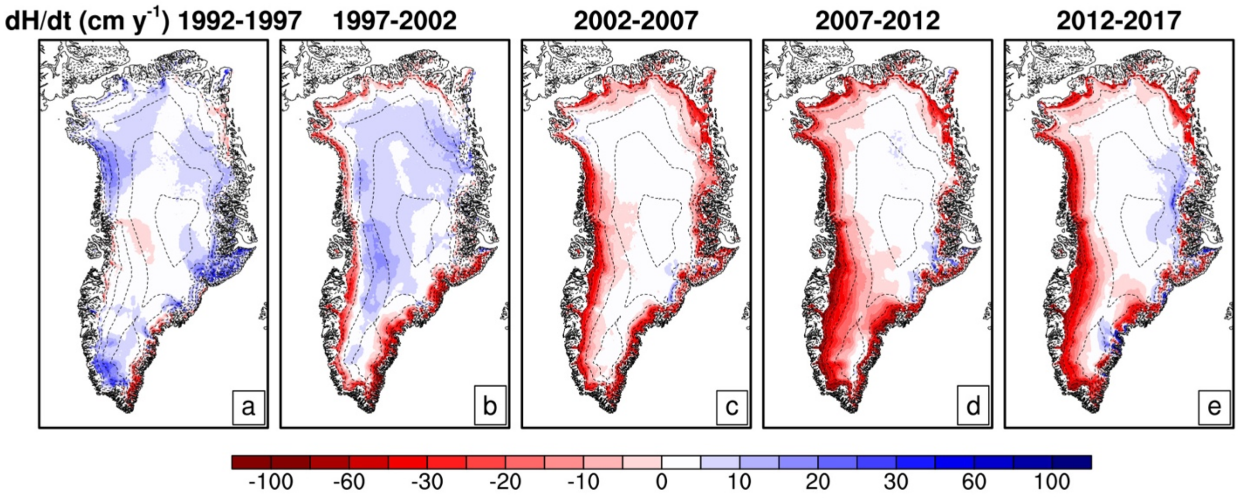

***Figure 4:*** *Surface elevation change (in cm y$^{-1}$) due to firn processes and surface mass balance, as computed by the firn model IMAU-FDM. It is assumed that dH/dt was on average zero during from 1960 to 1980, the last decades for which the total mass balance of the Greenland Ice Sheet is assessed to be in (near) balance. The ice sheet interior has been thickening in the period 1992-2002, whereas the lower-elevated parts of the ice sheet started thinning from the late 1990s onward, up to present-day.*

## List of publications/reports from the project with complete references

Noël, B.P.Y., W.J. van de Berg, S. Lhermitte and M.R. van den Broeke, accepted: Rapid ablation zone expansion amplifies north Greenland mass loss, *Science Advances*, accepted.

## 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 future plans for 2019 are drafted in the 2019 progress report. Plans for 2020 as proposed in the special project proposal for 2020.

### 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, https://doi.org/10.5194/tc-12-1643-2018.