SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Present and future climate of Antarctica and Greenland modelled with RACMO2.
Computer Project Account:	spnlbreg
Start Year - End Year :	2017- 2017
Principal Investigator(s)	Dr. W. J. van de Berg
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Other Researchers (Name/Affiliation):	Melchior van Wessem, Carleen Tijm-Reijmer, Brice Noël, Stan Jakobs, Christiaan van Dalum, Stefan Ligtenberg (all UU/IMAU) Bert van Ulft and Erik van Meijgaard (KNMI)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

Sea level rise due to significant mass loss from the Antarctic Ice Sheet (AIS) and the Greenland Ice Sheet (GrIS) is one of the largest threats of projected climate change. In this project, updated and improved estimates of the recent and future contribution of surface mass loss from the AIS and GrIS have provided using the polar version of the regional climate model RACMO2. These simulations also allows to understand the regional drivers of glacial changes and the model output is aimed to be used in various research fields, e.g. constraining mass fluxes on ice sheets, glaciers and ice stream; estimating current fresh water fluxes into the ocean or estimating accumulation and temperature driven thickness changes in the firn layer of ice sheets.

Summary of problems encountered

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

No problems were encountered in using ECFS, HPCF and the regional climate model RACMO2.
However, we were planning to use CESM2 forcing to drive our future climate simulations. The release of this updated version, which was planned to be early 2017, was delayed gradually. Eventually, the code of CESM2 was released in June 2018. As it was long very unclear when CESM2 could be used – and the planned RACMO2 simulations would be carried out shortly after the CESM2 delivery – a timely call on migrating resources to 2018 could not be made. The planned simulations will be carried out in 2018.

Experience with the Special Project framework

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

Application procedure and progress reporting are well organized.

Summary of results

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

Overview of RACMO2 results obtained in 2017

In 2017, we updated and improved our estimates of historical surface mass balance (SMB) of the Greenland and Antarctic Ice Sheets (GrIS and AIS) and did detailed simulations of the SMB for the Antarctic Peninsula, the coastal zone of Dronning Maud Land, Antarctica and Svalbard. For these simulations the polar version of the regional climate model RACMO2, version 2.3p.2 have been used. Most of the data is already used in publications of project members and shared with other researchers, increasing the scientific impact of the computational efforts. Most clear example of the scientific and societal impact of this research is provided by our contribution to the recent Nature paper (the IMBIE team, 2018). This paper shows that all available observational products give a threefold increase of mass loss from the Antarctic Ice Sheet in the last decade, disproving the longstanding assumption, e.g. in the latest IPCC report, that the contribution of the Antarctic Ice Sheet to future sea level rise is limited or negligible.

Greenland Ice Sheet

In 2018, we completed a reanalysis driven simulation covering 1958 to 2017 for Greenland on 11 km resolution using the latest version of RACMO2. These model results have been statistically downscaled to a 1 km grid following the procedure described in Noël et al (2016) and published in Noël et al (2018). Furthermore, a simulation on 5.5 km resolution has been started at the end of 2017. This run has been completed in 2018 and the results will be discussed in the 2018 progress report.

As the polar version 2.3p2 is primarily a retuning of the polar model version 2.3p1, the differences in modelled SMB reflect these different chances (Figure 1). Firstly, the critical cloud content, which determines when the precipitation generation process becomes efficient, has been increased, which generally delays precipitation inland as moisture removal is lost slower. As a result, the SMB is increased in the interior of Greenland. Furthermore, reducing the estimated impurity content of snow lowered the modelled melt in the percolation zones and upper ablation zones of the GrIS. Finally, the albedo of ice, which is prescribed from satellite observations, has been updated. This led to increased ablation for most of the glacier margin. All these changes led in general better estimates of modelled surface climate, snow albedo and SMB. An example of this improved SMB is shown in Figure 1c, displaying the updated SMB for 1976-2001 for Zachariae and Nioghalvfjerdsbrae glacier basins (within yellow lines in Fig. 1a). The SMB modelled by version 2.3p2 matches much better the ice discharge estimates for these glaciers. Given the stable state of these glaciers prior 2000, ice discharge and the SMB must be close to balance, hence the SMB was most likely underestimated in the older version.

The modelled climate is subsequently fed into the IMAU firn densification model (IMAU-FDM), a model that aims to provide the best possible description of the snow and firn layer over ice sheets. IMAU-FDM results driven by RACMO2.3p2 show a much better agreement with in situ observations, in particular near the equilibrium line where the firn layer plays a very distinctive role in partially buffering meltwater. In the new model version, melt in the percolation zone is reduced, lowering the equilibrium line and elevation down to which firn is modelled, strongly improving the agreement with observations (Fig. 2c,d). Furthermore, the subsurface firn heating by refreezing near the equilibrium line is now represented well while it was largely absent in the previous version (Fig. 2e,f).

Both the modelled SMB as firn changes are used for estimating the mass loss from the GrIS (e.g. McMillan et al, 2016). Firstly, this mass change is given by SMB-D, in which D represent the ice discharge into the ocean. Although this method has a relatively larger uncertainty than other methods, it allows for detailed physical and regional analysis as it separates the contributing processes. Secondly, firn changed modelled by IMAU-FDM are used to disentangle firn changes and mass changes from satellite altimetry data.

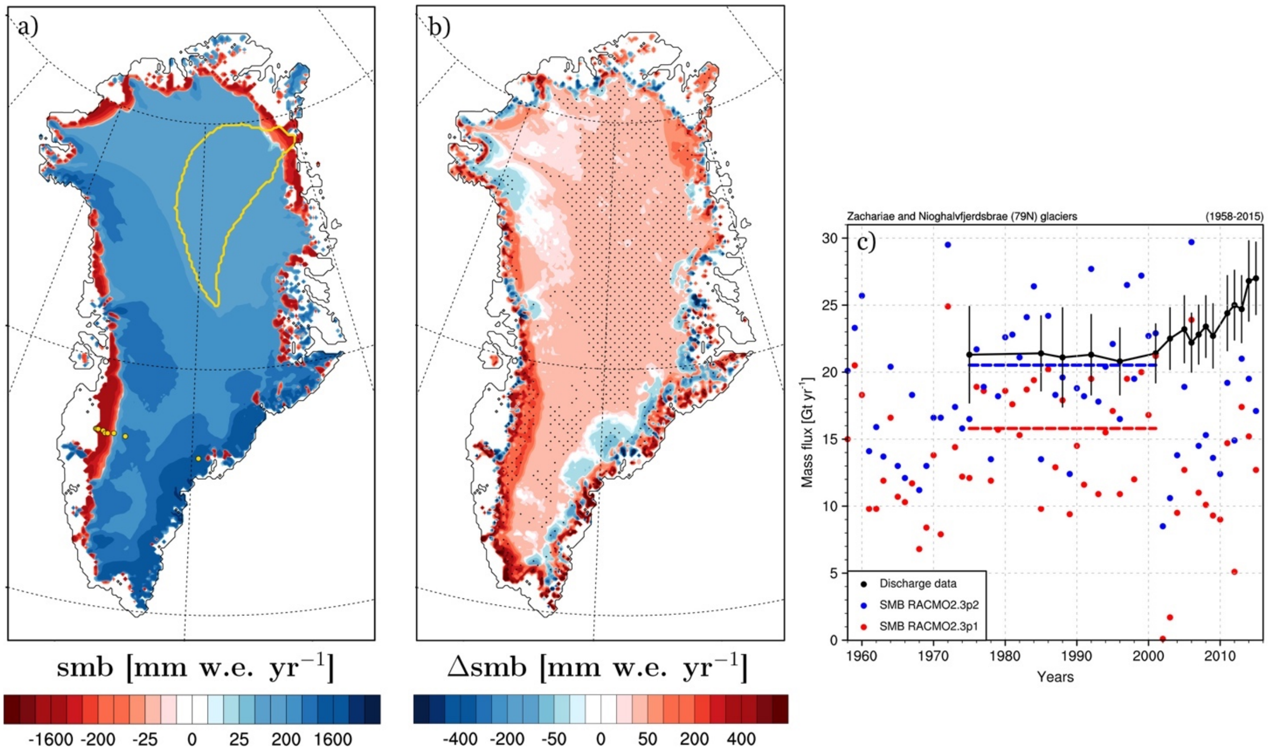

Figure 1: ***a)*** *Mean modelled SMB for 1958-2015 with RACMO2, version 2.3p2 and* ***b)*** *difference with modelled SMB with version 2.3p1. Regions with significant changes are dotted.* ***c)*** *Modelled basin-integrated annual SMB with RACMO2, version 2.3p2 and 2.3p1 are shown with blue and red dots, respectively. The black line is the estimated ice discharge from these two glaciers (Mouginot et al. 2015). Figures taken from Noël et al (2018).*

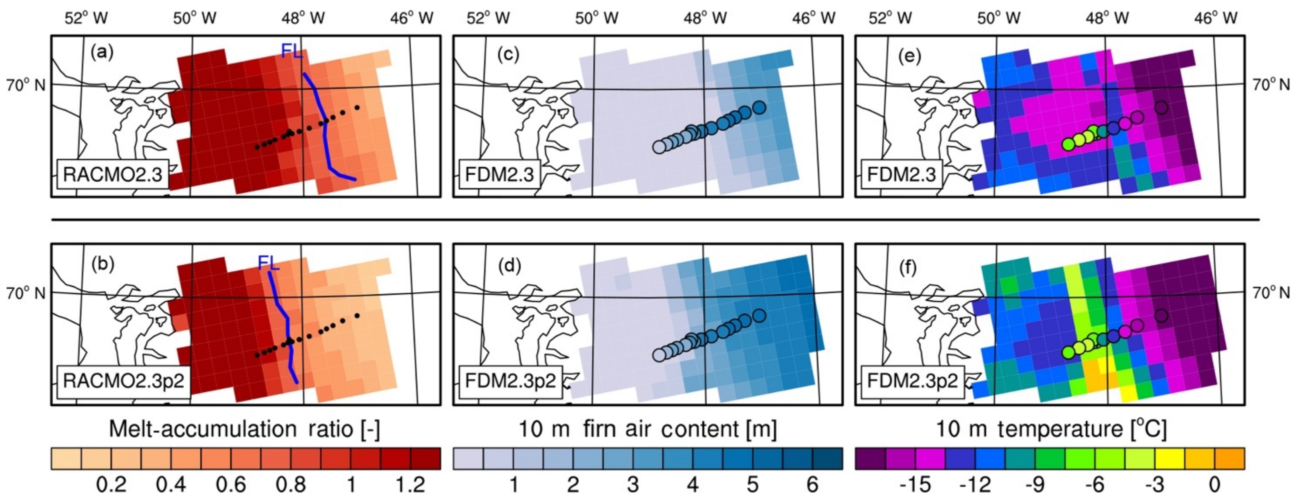

Figure 2: *Evaluation of simulated firn air content and 10 m firn temperature with observations along a transect in the western Greenland percolation zone (near yellow dots in Figure 1):* ***(a,b)*** *1990-2009 melt-accumulation ration as simulated by RACMO2,* ***(c,d)*** *upper 10 m firn air content as simulated by IMAU-FDM (shaded grid cells) and from firn core observations (circles, Harper et al, 2012);* ***(e,f)*** *Average 10 m firn temperature as simulated by IMAU-FDM (shaded grid cells) and from thermistor string measurements (circles, Humphrey et al, 2012). Figure taken from Ligtenberg et al (2018).*

Antarctic Ice Sheet

A new reanalysis driven simulation of whole Antarctica on 27 km resolution, covering 1979-2016 has been carried out in 2017, analysed and published in Van Wessem et al (2018). Furthermore, firn processes are derived in detail by a subsequent IMAU-FDM run. Below a few results of this simulation are highlighted.

Figure 3 shows the changes in modelled surface mass fluxes. Similar to the new GrIS results, accumulation is increased on the interior ice sheet (Fig. 3a). However, dynamical feedbacks also clearly have appeared, e.g. reducing the precipitation over the Filchner-Ronne Ice Shelf sector of West Antarctica (30-90° West, 75-90° South). In Antarctica, less snow drift is simulated, a result of a retuning of the snow drift model which appeared to generate too large snow drift transport fluxes. Lesser snow drift transport fluxes result also in generally less snow drift sublimation. In Antarctica, snowmelt is slightly enhanced in the new run, following observations (not shown). The changes in SMB (Fig. 3d) follow closely the changes in total precipitation, modulated by changes in the sublimation. Snowmelt (changes) has negligible impact on the SMB as almost all melt water refreezes locally.

This updated SMB and firn estimates are used, for example, in the 2018 key publication on the recent mass loss of the AIS (the IMBIE team, 2018). Our SMB estimates allow to separate the mass changes due to interannual variability in precipitation of the impact of enhanced ice discharge primarily induced by ocean warming. As there is no trend in SMB over the period 1979-2017, the recent increasing mass loss from the AIS is dominated by changes in solid-ice discharge in the ocean.

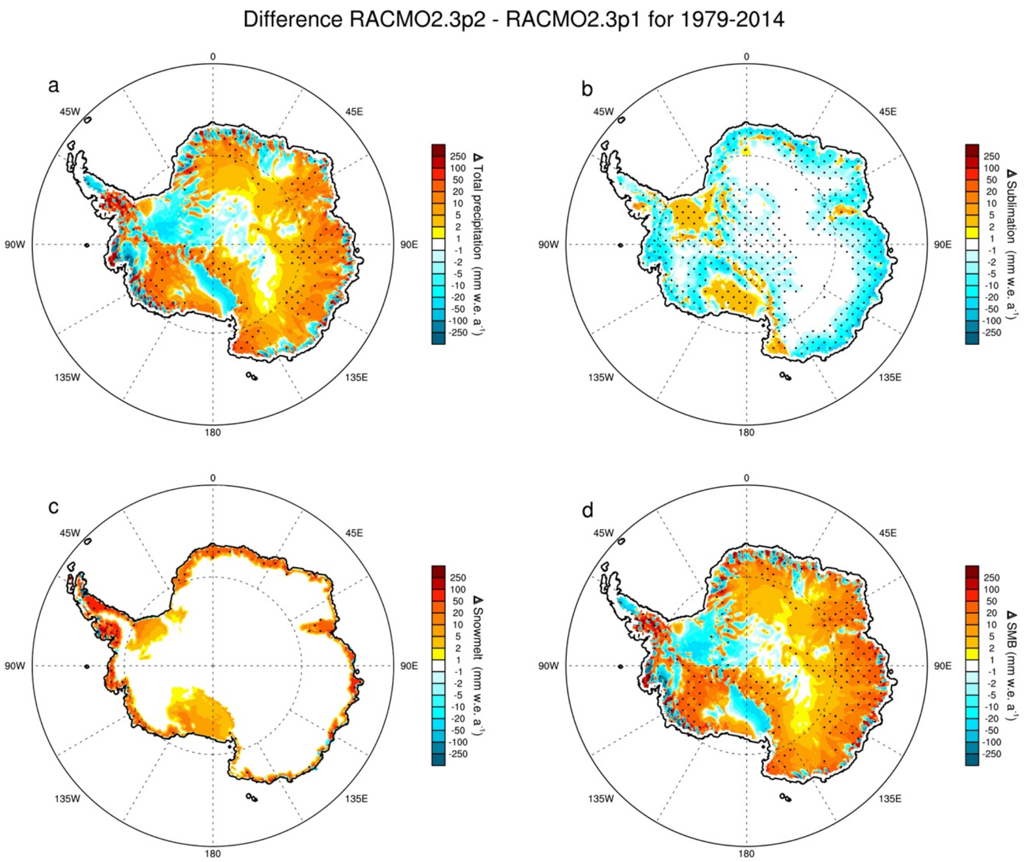

***Figure 3**: Annual average (1979-2014) difference (RACMO2.3p2-RACMO2.3p1) of **a)** total precipitation (snow and rain), **b)** total drifting snow and surface sublimation, **c)** snowmelt and **d)** SMB. Areas where the difference exceeds 1 standard deviation of the difference are stippled. Figure taken from Van Wessem et al (2018).*

Antarctic Peninsula

Using the updated model version, an ERA-Interim driven, high-resolution simulation covering 1979-2016 for the Antarctic Peninsula has been completed. This simulation updates a similar simulation using version 2.3p1. Apart from the expectation that the model update would improve the estimated SMB and melt fluxes, this simulation was required as we spotted an error in the topography of the 2.3p1 run. In the older run, the topography and land-sea-mask were misallied by one grid box. As a result, much of the melt at the northwestern side of the Antarctic Peninsula was not resolved in the older run.

Figure 4 compares integrated SMB with ice discharge from glaciers not affected by the topographic masks errors. If integrated SMB equals ice discharge the glacier is in balance. Similar as for mainland Antarctica (fig. 3d), the SMB has increased slightly and the agreement with ice discharge data has improved marginally. The results of this simulation are published in Van Wessem et al (2018).

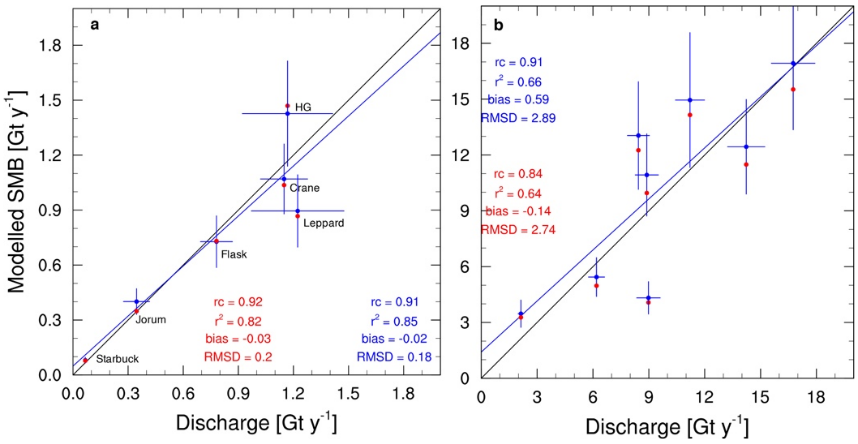

***Figure 4**: Modelled RACMO2.3p2 (blue) and RACMO2.3p1 (red) integrated average (1979-2016) SMB as a function of glacial discharge estimates from **a)** the Larsen B embayment (Wuite et al, 2015) and **b)** the George VI embayment (Hogg et al, 2017). Horizontal error bars represent the uncertainty in the discharge estimates, vertical bars the interannual variability of RACMO2.*

Dronning Maud Land

The final high-resolution run carried out for the Antarctic continent covered the ice shelves in Dronning Maud Land. Lenaerts et al (2017) showed that melt and meltwater is abundantly present at the landward side of ice shelves in Dronning Maud Land. This run aims to improve the modelled estimates of snowmelt. The results are currently being analysed and a publication is prepared. Figure 5 shows, as an example, the modelled SMB, highlighting the amount of detail that is added by the fivefold increase in resolution. For example, the local impact of snowdrift transport is much better resolved, leading to local increases or reductions of the SMB.

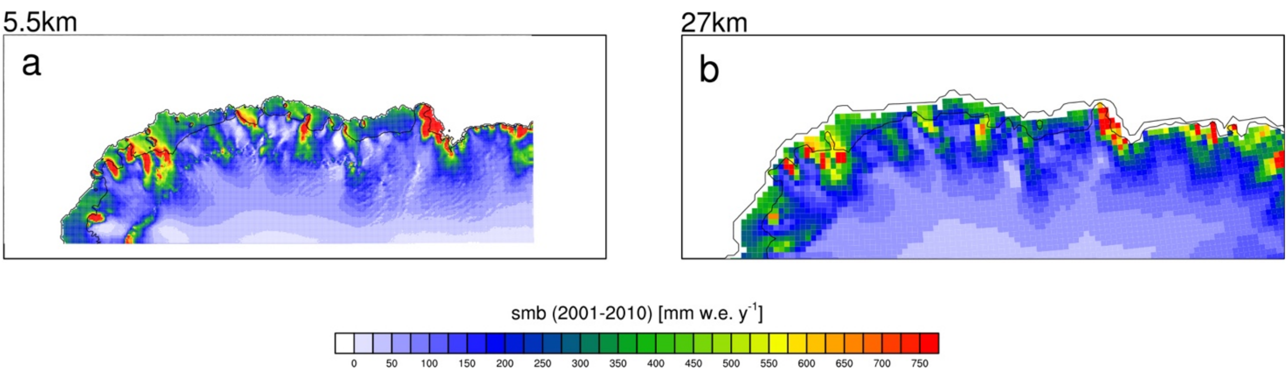

***Figure 5:** Mean modelled SMB (1979-2016) in Dronning Maud Land, Antarctica, using **a)** a 5.5 and **b)** 27 km resolution grid.*

Svalbard

In 2017 new simulations for Svalbard had been carried out. Here, a two-step approach has been taken. Firstly, RACMO2 is run on 11 km on a domain expanding well away from Svalbard, and this run has been driven by ERA-40 (1958-1978) and ERA-Interim (1979-2016) data. This run is subsequently used to force a very-high resolution RACMO2 run on 3.5 km focussing on Svalbard, allowing to resolve many glacier valleys. These latter results have been statistically downscaled to 500 m topography following the procedure described in Noël et al, 2016.

Figure 6 gives an overview of the model results. The SMB of Svalbard (Fig. 6a) shows that spatial precipitation variability and elevation-dependent runoff both determine the SMB. The simulation suggests that the glaciers in west and south Svalbard are much more out of balance than those in central and east Svalbard. Evaluation against the rather scattered in situ observations (Fig. 6b) shows that the downscaled product rather faithfully represents the observed variability but that improvements are still possible. Nevertheless, very good agreement exists between the integrated SMB and observed mass trends using satellite gravimetry (GRACE) and satellite altimetry (Cryosat-2 and ICESat) as shown in Figure 6c.

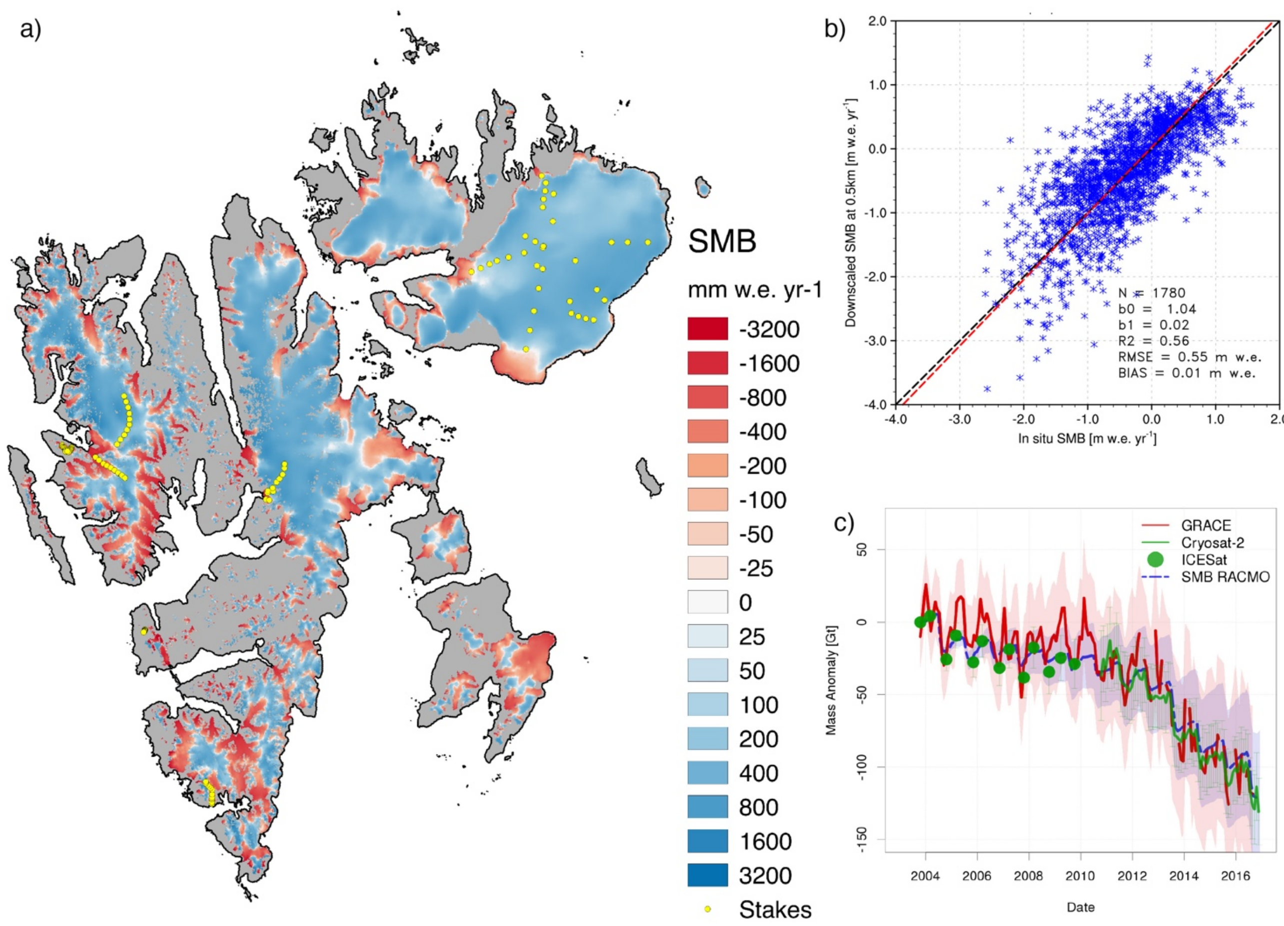

Figure 6, a) *statistically downscaled SMB to a 500 m resolution topography and glacier outline. The observations used for calibration are located with yellow dots.* ***b)*** *Scatter plot between observed in situ SMB and statistically downscaled SMB.* ***c)*** *SMB time series of observed mass trends of Svalbard using various remote sensing techniques.*

Implementation of narrowband snow albedo scheme in RACMO2

In 2017 the implementation is started to include the spectral snow albedo model TARTES (Libois et al, 2013) into RACMO2. For this aim, a coupler has been designed that links spectral albedo values to the narrowband radiation scheme in RACMO2. This coupling is non-trivial; the spectral albedo of snow and ice, and the downwelling shortwave radiation are both highly wavelength dependent. Hence, the effective narrowband albedo is often distinctively different to the albedo of the median band wavelength. The coupler makes use of the fact that the wavelength, with an albedo equal to the effective narrowband albedo for that specific situation, is primarily determined by the solar zenith angle and the optical thickness of clouds. By deriving these representative wavelengths for each band of the radiation scheme as function of atmospheric conditions, the narrowband albedo can be estimated with a spectral albedo model. This coupler has been tested offline; the implementation of TARTES and the coupler into RACMO2 reaches now (June 2018) its completion.

Figure 7 shows example results of offline tests. Differences with broadband occur for clear sky and high solar zenith angle and highly inhomogeneous snow columns. In particular for low specific surface area (SSA), hence larger snow grains due to metamorphism or melting, quite different result are obtained from the three different albedo schemes.

A paper describing the coupling procedure and offline results will be submitted soon. Furthermore, it is expected that this narrowband albedo scheme will lead to an improved representation of albedo.

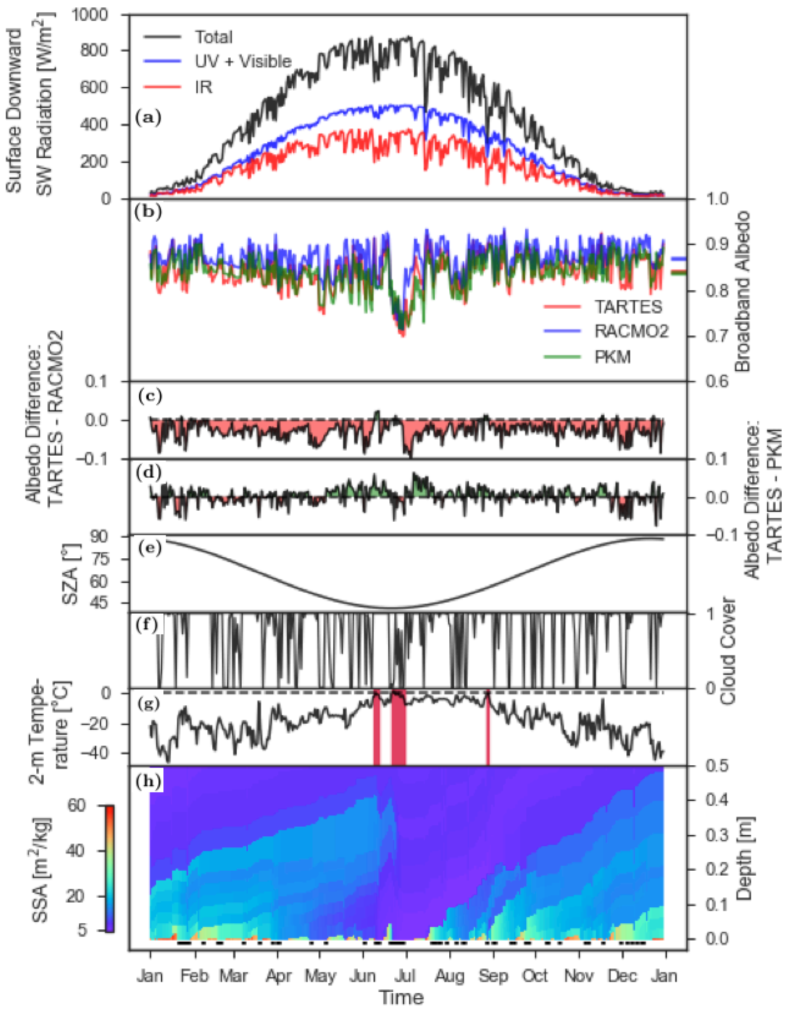

Figure 7: *Time series for a point on the southern dome of Greenland for 2007. Only data for 15 UTC (12:00 local time) are shown to remove clutter from the daily cycle. From top to down:* ***a)*** *surface downwelling shortwave flux;* ***b)*** *broadband albedo from TARTES and two broadband schemes,* ***c)*** *differences between TARTES and the currently implemented two-layer albedo scheme;* ***d)*** *differences between TARTES and a multilayer version of the RACMO2 albedo model;* ***e)*** *solar zenith angle;* ***f)*** *cloud cover;* ***g)*** *2-m temperature, with in red bars indicating melt days;* ***h)*** *the specific surface area (SSA) of the snow layers as a function of depth, with the horizontal black bars at the bottom indicating moments without a top fresh snow layer.*

Overview of used computer resources

Model	Simulation	Resources (million SBU) Requested	Used
RACMO2	Greater Greenland, 11 km, 1958-2016		4.5
	Greenland, 5.5 km, 1958-2016	14.0	7.7[a]
	Antarctica, 27 km, 1979-2016	2.2[b]	0.0[c]
	Amundsen Sea Sector (Antarctica), 5.5 km, 1979-2016	4.9	Completed in 2016
	Dronning Maud Land (Antarctica), 5.5 km, 1979-2016		4.5
	Antarctic Peninsula, 5.5 km, 1979-2016		4.0
	Svalbard, 11 & 3.5 km, 1958-2017		4.2
	Model development		0.1
IMAU-FDM	Antarctica (1979-2016) & Greenland (1958-2016)		3.6
RACMO2	Greenland, 11 km, climate projections	11.4	Postponed to 2018
	Antarctica, 27 km, climate projections	6.0	Postponed to 2018
Total		40.0	28.6

[a] This run was not yet completed at the end of 2017
[b] The run was planned to be run at 18 km resolution
[c] These costs were accidentally accounted on the nlcko budget

References not listed below:

Harper, J., N. Humphrey, W.T. Pfeffer, J. Brown and X. Fettweis, 2012: Greenland ice-sheet contribution to sea-level rise buffered by meltwater storage in firn, *Nature*, **491**, 240–243.

Hogg, A. E., A. Shepherd, S.L. Cornford, K. Briggs, N. Gourmelen, J.A.. Graham, I. Joughin, J. Mouginot, T. Nagler, A.J. Payne, E. Rignot and J. Wuite, 2017: Increased ice flow inWestern Palmer Land linked to ocean melting, *Geophys. Res. Lett.*, **44**, 4159–4167, https://doi.org/10.1002/2016GL072110.

Humphrey, N.F., J.T. Harper and W.T. Pfeffer, 2012: Thermal tracking of meltwater retention in Greenland's accumulation area, *J. Geophys. Res.*, **117**, F01010, https://doi.org/10.1029/2011JF002083.

Lenaerts, J. T. M., S. Lhermitte, R. Drews, S. Ligtenberg, S. Berger, V. Helm, C. Smeets, M.R. van den Broeke, W.J. van de Berg, E. Van Meijgaard, M. Eijkelboom, O. Eisen and F. Pattyn, 2016: Meltwater produced by wind-albedo interaction stored in an East Antarctic ice shelf, *Nature Climate Change*, **7**, 58–62, https://doi.org/10.1038/nclimate3180, 2016a.

Libois, Q., G. Picard, J.L. France, L. Arnaud, M. Dumont, C.M. Carmagnola and M.D. King, 2013: Influence of grain shape on light penetration in snow. *Cryosphere*, **7**,1803-1818.

Mouginot, J., E. Rignot, B. Scheuchl, I. Fenty, A. Khazendar, M. Morlighem, A. Buzzi and J. Paden, 2015: Fast retreat of Zachariæ Isstrøm, northeast Greenland, *Science*, **350**, 1357–1361.

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.

Wuite, J., H. Rott, M. Hetzenecker, D. Floricioiu, J. De Rydt, G.H. Gudmundsson, T. Nagler and M. Kern, 2015: Evolution of surface velocities and ice discharge of Larsen B outlet glaciers from 1995 to 2013, *The Cryosphere,* **9**, 957–969, https://doi.org/10.5194/tc-9-957-2015, 2015.

List of publications/reports from the project with complete references

Listed are the papers in which the data from runs carried out in 2017 are published

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.

Noël, B.P.Y., W.J. van de Berg, J.M. van Wessem, E. van Meijgaard, D. van As, J.T.M. Lenaerts, S. Lhermitte, P. Kuipers Munneke, C.J.P.P. Smeets, L.H. van Ulft, R.S.W. van de Wal and M.R. van den Broeke, 2018: Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 1: Greenland (1958-2016), *The Cryosphere*, **12**, 811-831.

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.

Five examples of 2017-2018 papers from non-IMAU researchers using (recent) RACMO data.

Kallenberg, B., P. Tregoning, J.F. Hoffmann, R. Hawkins, A. Purcell and S. Allgeyer, 2017: A new approach to estimate ice dynamic rates using satellite observations in East Antarctica, *The Cryosphere*, **11**, 1235-1245.

Kingslake, J., J.C. Ely, I. Das and R.E. Bell, 2017: Widespread movement of meltwater onto and across Antarctic ice shelves, *Nature*, **544**, 349-352.

McMillan, M., A. Leeson, A. Shepherd, K. Briggs, T.W.K. Armitage, A. Hogg, P. Kuipers Munneke, M. van den Broeke, B. Noël, W.J. van de Berg, S. Ligtenberg, M. Horwath, A. Groh, A. Muir and L. Gilbert, 2016: A high-resolution record of Greenland mass balance, *Geophys. Res. Lett.*, **43**, 7002–7010, doi:10.1002/2016GL069666

Martin-Español, A., J.L. Bamber and A. Zammit-Mangion, 2017: Constraining the mass balance of East Antarctica, *Geophys. Res. Lett.*, **44**, 4168-4175, doi:10.1002/2017GL072937.

The IMBIE team, including M.R. van den Broeke, B.P.Y. Noël, W.J. van de Berg and J.M. van Wessem, 2018: Mass balance of the Antarctic Ice Sheet from 1992 to 2017, *Nature*, **558**, 219-222.

Please note that our current and past work is widely used within the research community. A Google scholar search using “RACMO2 and Antarctica or Greenland” gives over 600 hits to articles, abstracts and presentations. From 2017 up to date (end of June 2018), about 80 publications have been published in which polar RACMO2 data is used.

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.)

Our plans for the remainder of 2018 are discussed in the 2018 SPNLBERG progress report. Proposed simulations for 2019 are discussed in detail in the request for computer resources for 2019.

Briefly, our plan for 2018 is to carry out RACMO2 simulation for Greenland (11 km) and Antarctica (27 km) driven by CESM2 output using CMIP6 settings. For each domain, these runs comprise of a 1980-2010 reference climate run and two 2010-2100 projections using the SSP1-26 and SSP5-85 scenarios. For 2019, it is proposed to carry out a 8 km resolution 1980-2100 reference and SSP5-85 simulation for the Antarctic Peninsula; a 5.5 km resolution 1957-2018 simulation for the three glaciated Russian Arctic Archipelagos using ERA5 or, if needed, older ERA reanalyses; further test and evaluation simulations of RACMO2 including the spectral albedo scheme TARTES and finally explore the opportunities to use HCLIM for polar research by various shorter kilometre-resolution for Svalbard.