SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	*High resolution regional modelling of contemporary and future polar climate and ice sheet surface mass balance*
Computer Project Account:	spnlberg
Start Year - End Year :	2022 - 2022
Principal Investigator(s)	Dr. W. J. van de Berg
Affiliation/Address:	Utrecht University (UU), Institute for Marine and Atmospheric Research Utrecht (IMAU) Princetonplein 5, 3584 CC, Utrecht The Netherlands www.imau.nl
Other Researchers (Name/Affiliation):	Dr. Melchior van Wessem Dr. Christiaan van Dalum Dr. Brice Noël Dr. Srinidhi Nagarada Gadde Dr. Kristiina Verro Maurice van Tiggelen Sanne van Veldhuijsen Max Brils (UU/IMAU) Dr. Carleen Reijmer Dr. Peter Kuipers Munneke Dr. Erik van Meijgaard (KNMI)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The long-term goal of the research supported by ECMWF special projects is to improve our understanding and model estimates of the climate of polar regions and to provide timely and reliable estimates of the surface mass balance and firn conditions of the two ice sheets. For these aims, we use primarily a polar optimized version of the regional climate model RACMO and refine the snow surface evolution with the firn densification model IMAU-FDM.
For 2022, we aimed to use the updated version of RACMO (2.4) and make new, ERA5 driven, simulations for the Arctic, Greenland, and Antarctica. Secondly, we aimed to apply to HCIM for the Antarctic Peninsula. Lastly, we planned to carry out detailed projections of the contemporary and future evolution of the firn layer of the two ice sheets during the 20th and 21st century using IMAU-FDM.

Summary of problems encountered

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

The specific project aims for 2022 have mostly not been met in 2022. The primary reason was that the development of RACMO, version 2.4, for which most of the budget was requested, took far more time than anticipated in 2021. The old RACMO version (version 2.3) relied on IFS cycle CY31R4 for the description of physical processes in the atmosphere, while version 2.4 uses IFS cycle CY47r1. Especially the complete overhaul of the coding structure in the IFS code, e.g., extensive use of in-code defined types, slowed down the coupling process. As a result, we failed to run any significant simulations in 2022.
The migration and upgrade of the ECMWF HPCF and data storage to Bologna in 2022 went slower than projected in 2021. Although it was communicated that in fall 2022 files on ECFS and MARS would be unavailable for multiple weeks if not timely measures would be taken, it caught us out. As a result, progress was hampered for about a month.
More troublesome is that a small fraction of the data stored at ECFS in Reading got lost during the migration to the new ECFS systems in Bologna. Due to the simultaneous change of machine, it was impossible to recreate these small bits of lost data, as recreating requires a bitwise equal version of the model. Therefore, these lost data fraction significantly reduced the scientific value of the simulations we performed in the last years.
Finally, the relatively slow retrieval (>week) of large amounts of data from ECFS (>10 Tb), inhibits sometimes usage of data stored at ECFS, as the effort to get data online is larger than the scientific benefit, for us or for our data users.

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, reporting, administration processes along with special projects are smooth.
The only point of improvement could be an earlier notification than in December that projects are approved or not. Because if the project is rejected, there is very limited time available to secure computer resources at alternative facilities and set-up our models without a lengthly disruption of our workflow.

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.)

For 2022, 200 million System Billing Units (SBU) of High Performance Computer Facilities (HPCF) were requested, of which 47.5 MSBU were consumed. The actual usage can be broken down to the following subprojects:

Regional Climate Modelling	
Operational simulations with RACMO, version 2.3p2	10.6 MSBU
Patagonia at 5.5 km resolution (1979-2021)	
Greenland at 5.5 km (extension into 2022)	
Antarctica at 27 km (extension into 2022)	
Testing and developing surface roughness parameterizations	9.1 MSBU
Improving snow drift parameterizations in RACMO	3.3 MSBU
Developing RACMO, version 2.4	2.0 MSBU
Adapting HCLIM for Antarctica	3.5 MSBU
Firn evolution modelling	
IMAU-FDM	19.0 MSBU
Renewing model product and assessing model uncertainties	
projections for Greenland (2015-2100)	
projections for Antarctica (2015-2100)	
Total usage	**47.5 MSBU**

Below we discuss these simulations or refer to the midterm report in case in the simulation has been carried out during the first half of 2022.

REGIONAL CLIMATE MODELLING

Operational simulations with RACMO

In 2022, we updated our simulation of the climate and surface mass balance (SMB), the sum of (solid) precipitation, sublimation and melt water runoff), for the Patagonian ice fields. Similar simulations had been carried out in 2013 and published by Lenaerts et al. (2014). Since then, both the quality of the reanalysis and RACMO has improved, while there is still scientific interest in our data. Therefore, we have rerun the simulation at 5.5 km for the Patagonian Ice Fields for the period 1979-2021, using ERA5 climate boundaries and the operational RACMO version (2.3p2). Preliminary results are shown in the ECMWF progress report (van de Berg 2022).

Furthermore, our operational estimates of the climate and SMB of Greenland, at 5.5 km resolution, and Antarctica, at 27 km resolution, have been extended into 2022. These simulations are short and therefore relatively cheap, but of great value for the scientific community, e.g., for mass budget studies of the Antarctic and Greenland ice sheets (Otosaka et al. 2023).

Finally, the modelled SMB (1979-2021) from the operational simulation for Antarctica has been statistically downscaled to a 2 km grid. This method has been developed for the Greenland Ice Sheet (GrIS) and works particularly well for elevation dependent SMB components like melt, refreezing, and runoff (Noël et al. 2016; Noël et al. 2019). The goal was to improve the representation of Antarctic-wide surface mass balance (SMB) and surface melt at very high spatial resolution (Fig. 1). Our results show good agreement with both in-situ (Stakes/AWS) and satellite (GRACE/QuikSCAT) measurements, highlighting the added value of this new product.

Next, we applied statistical downscaling to three warming scenario projections, SSP1-2.6, SSP2-4.5 and SSP5-8.5, 1950-2100, from CESM2-forced RACMO2.3p2 simulations at 27 km, to investigate the impact of spatial resolution on future Antarctic melt by 2100 (Fig. 2). These results are the core of a manuscript currently in review (Noël et al. in review).

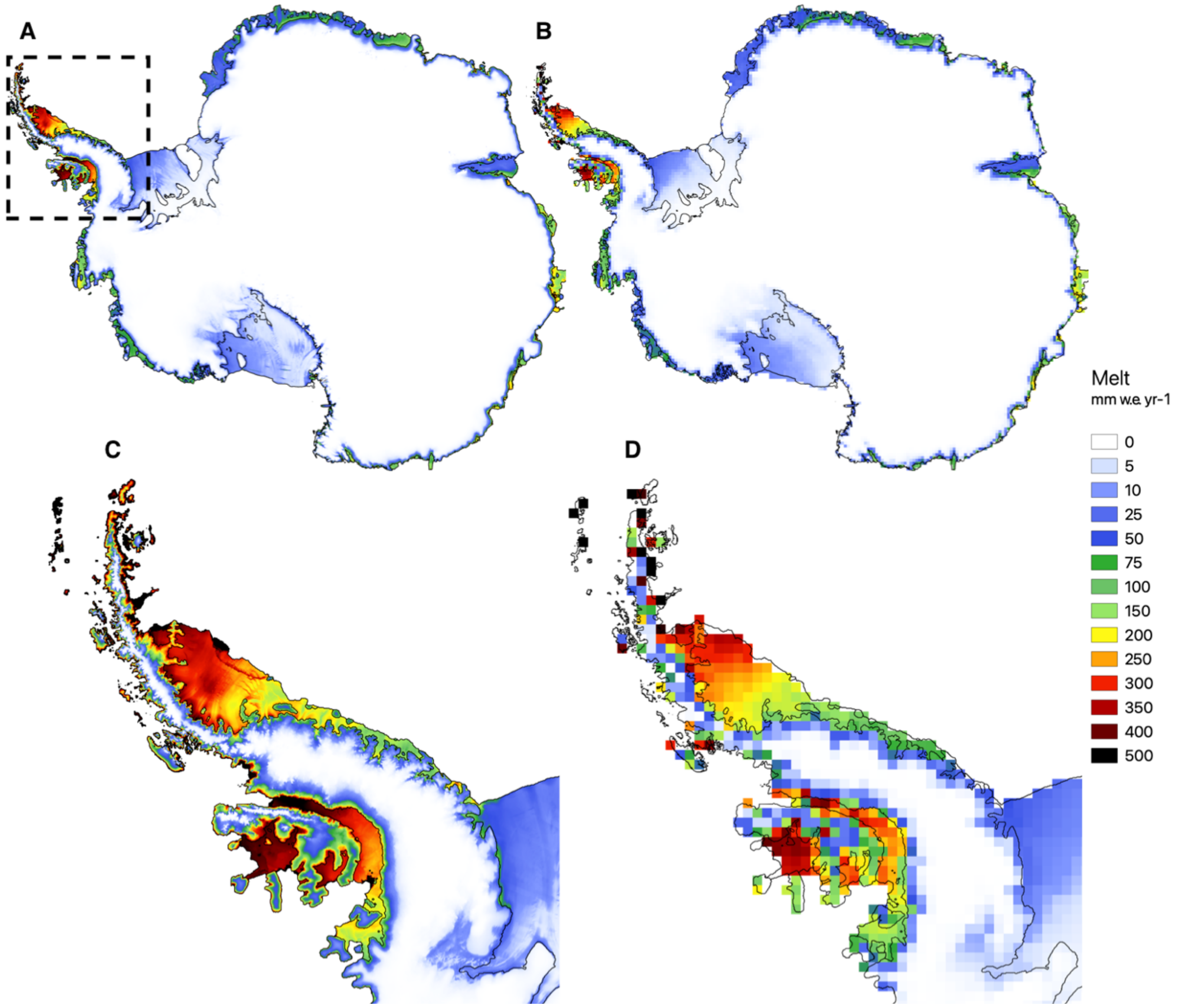

Figure 1: *Annual mean surface melt (1979-2021) across the Antarctic ice sheet / ice shelves **A** statistically downscaled to 2 km, and **B** as modelled by native RACMO2.3p2-ERA5 at 27 km spatial resolution. **C** and **D**, zoom in on the Antarctic Peninsula (dashed line in **A**) at 2 km and 27 km resolution, respectively.*

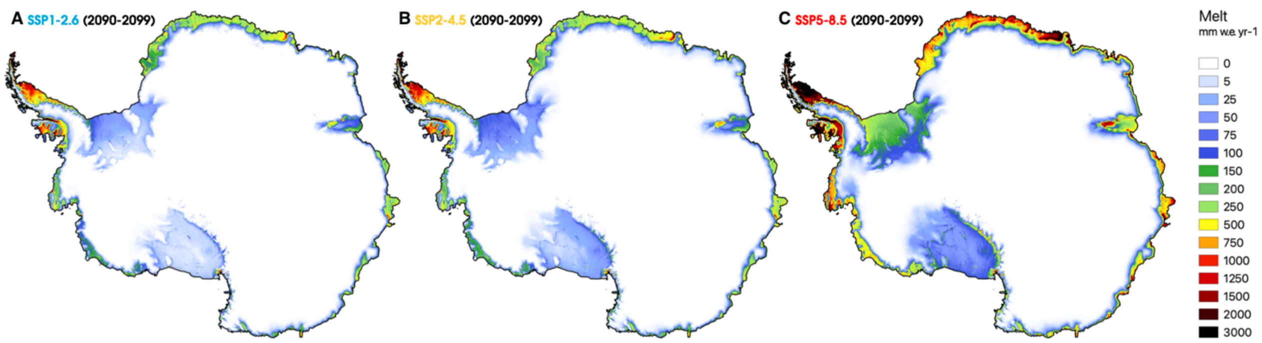

Figure 2: *Annual mean surface melt at 2 km resolution projected under different warming scenarios for the period 2090-2099. Scenarios include **A** low-end SSP1-2.6, **B** moderate SSP2-4.5, and **C** high-end SSP5-8.5 warming.*

Testing and developing surface roughness parameterizations

It is known that the roughness of an ice sheet varies greatly. Snow covered surfaces are very smooth, while when bare ice surface, the surface gets rougher. In RACMO, we use uniform but different roughness lengths for momentum (z_{0m}) for snow and ice surface over ice sheet. This is a reasonable assumption for snow, but the roughness in the ablation zone varies greatly in space in time. It is a reasonable assumption that during equal melting conditions, a rougher surface induces a higher downward turbulent energy flux and thus experiences more melt.

The first results of numerical experiments with RACMO are discussed in the our progress report of 2022 (van de Berg 2022). Further analysis showed that the sensible and latent heat flux over ice in RACMO is rather insensitive for variations in z_{0m}, as changes in z_{0m} are directly balanced by changes in the roughness lengths for heat and moisture, which are dynamically derived. The results are analysed in detailed in the PhD thesis of Maurice van Tiggelen (van Tiggelen 2023, chapter 6). Furthermore, a map of the surface roughness of the GrIS, via calibrating ICESat-2 data, has been derived (van Tiggelen 2023, page 149).

Improving snow drift parameterizations in RACMO

A blowing snow model had been implemented in RACMO2 in 2011 and has been subsequently used for projections of blowing snow in both Antarctic and Greenland ice sheets. However, the blowing snow model failed when compared to the recent blowing snow observations from East Antarctica (Amory 2020), which necessitated an update. In 2022, we picked up the rectification of the blowing snow model in RACMO and evaluated the results of the updated model against in-situ observations from site D47 in East Antarctica (location: 67.4° S, 138.7° E).

In RACMO, we use the bulk (non-spectral) version of the PIEKTUK model (Déry and Yau 1999), which employs an evolution equation for the mixing ratio of blowing snow q_b (kg/kg) and an additional equation for the evolution of snow particle number concentration *N*. This is the double-moment version of the PIEKTUK model (PIEKTUK-D, Déry and Yau (2001)). Five major updates in the implementation of PIEKTUK in RACMO have been applied:

1. In RACMO, only 12 ice particle size bins were used, with a constant particle bin size Δr = 4 μm. Therefore, size bins with a mean ice particle radius greater than 50 μm were excluded, which caused the unexpected variation of blowing snow fluxes. To overcome this limitation, we now use 16-particle size bins with an exponentially increasing Δr. This allows us to include all relevant particle size classes with particles of mean radius for each bin from 2 to 300 μm.
2. To reduce the computational expenses, we have reduced the vertical levels to 16, with 8 logarithmically varying levels up to the lowest RACMO model level.
3. We found that the PIEKTUK model when coupled with RACMO is also highly sensitive to the model time step. To overcome the large time steps used in RACMO we now use 5 sub-steps with a time step of 10 seconds and the fluxes from the last sub-step are taken as the representative flux for the whole RACMO model step.
4. In RACMO, the bulk sublimation rate S_b was used to calculate an integrated blowing snow sublimation flux and added this integrated moisture flux at the surface. While this approach works reasonably in obtaining SMB estimates, it is not completely physical since it limits the effect of blowing snow sublimation to the surface. To rectify this error in representation, we now add blowing snow sublimation rate (S_b) and latent heat due to blowing snow ($L_s S_b / C_p$) as tendencies to the prognostic equations of atmospheric water vapour and temperature, respectively.

5. In RACMO, snowdrift was modelled when the friction velocity was greater than the threshold friction velocity i.e. $u_* > u_{*t}$ and Equation $q_{salt} = c_{salt}(1 - (u_{thr}/U_{fml})^{2.59})$ was used to estimate the saltation flux. This parameterization caused sharp variations in the saltation flux in RACMO and was therefore not optimal. Therefore, this formulation was replaced by Equation $q_{salt} = \frac{e_{salt}}{g h_{salt}}(u_*^2 - u_{*t}^2)$, which produces smooth variations of q_{salt} and much widely used in literature.

We evaluate the performance of RACMO updated in predicting the near-surface wind speed, temperature, relative humidity, and snow transport fluxes for the years 2010--2012. Site D47 is located in the katabatic wind zone of the Antarctic coast and therefore receives high mean wind speeds. Figure 3(a) shows the observed 2-meter wind speed variation against simulated wind speed. Similar to the previous version, the RACMO updated underpredicts the near-surface wind speeds with a root-mean-squared error (RMSE) of 3.2 m/s. The coefficient of determination (R^2) is approximately 0.76, indicating that RACMO resembles the synoptic evolution of the wind strength well. Figure 1(b) compares the observed 2-meter air temperature T_{2m} against the simulated T_{2m}. We observe that all three simulations have a small positive temperature bias. The variability is modelled well, with an RMSE of 3 K, and a high $R^2 = 0.91$. Figure 1(c) presents a comparison of observed relative humidity with respect to ice against the simulated relative humidity. Though there is significant spread in the data, the RMSE is 6.9% and is $R^2 = 0.91$, Figure 1(c) shows a significant match between the observed and simulated data. In Figure 1(d) we present the comparison of simulated near-surface snow transport flux with observed flux. With versions RACMO2.3p1 and RACMO2.3p2 (van Wessem et al. 2018), simulated Q_T data had low coefficient

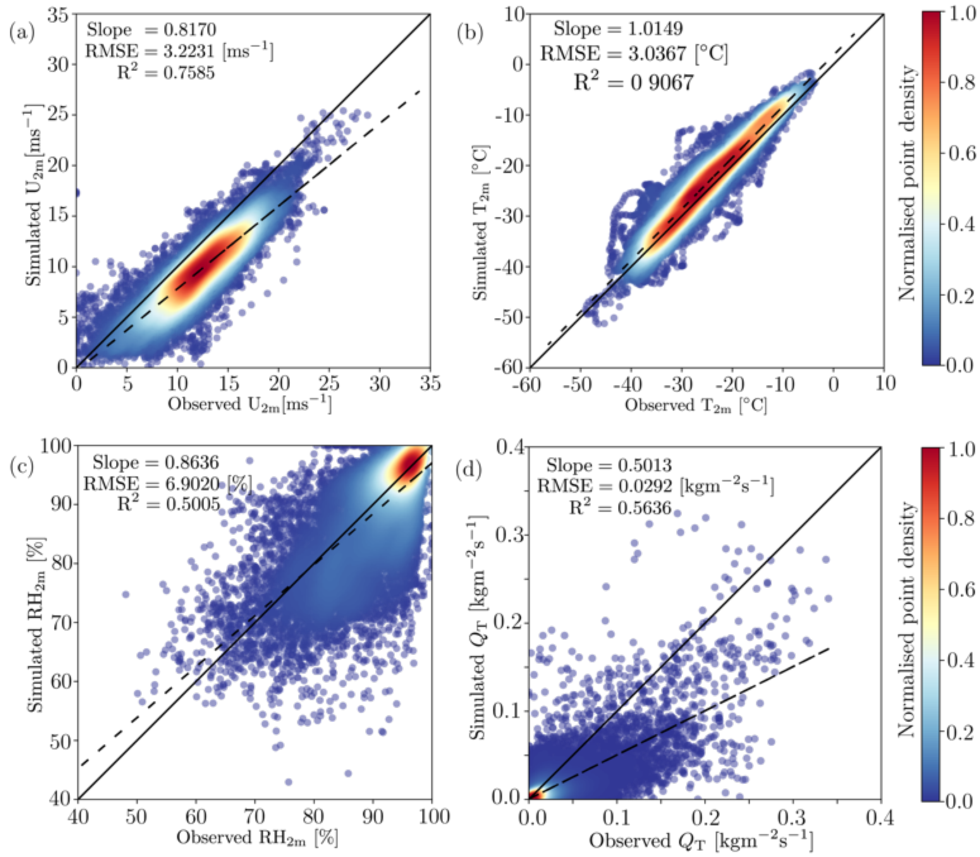

Figure 3: *Density scatter plots of observed and simulated near-surface quantities with RACMO at site D47,* ***(a)*** *2-meter wind speed,* ***(b)*** *2-meter temperature,* ***(c)*** *2-meter relative humidity w.r.t. ice and* ***(d)*** *Blowing snow flux. Solid lines represent the 1:1 line and the dashed lines represent the best-fit line. The colors represent the normalized point density from low (0.0, blue) to high (1.0, red).*

of determination $R^2 = 0.22$ and 0.33, respectively. In contrast, with RACMO updated, we have a significant match between the observed and simulated fluxes (figure 1(d)) with a coefficient of determination $R^2 = 0.56$. This clearly indicates the changes introduced in RACMO significantly improve its ability to reliably predict the blowing snow fluxes.

Development of RACMO version 2.4

As mentioned above, the development of RACMO2.4, a major model update, continued in 2022. RACMO2.4 includes new physics packages from the ECMWF IFS cycle 47r1, updating the previously operational cycle 33r1 packages. RACMO2.4 includes a new cloud scheme, a multilayer snow module for tundra snow, a lake model, updated ice masks and more. In 2022, code development has been finished and first tests have been carried out. First tests show promising results, but finalizing the code took longer than expected. The three planned large experiments have, therefore, been postponed to 2023 and computer resources used for this project are far lower than anticipated.

The current status of the development, testing, tuning and deployment of RACMO2.4 is discussed in the ECMWF special progress report of the project "Bipolar regional climate projections".

Adapting HCLIM for Antarctica

Testing HCLIM in the Antarctic domain started in August 2022. Experiments at 2.5 km resolution covering short periods, a few weeks to a few months, of the Antarctic Peninsula and the Weddell Sea have been continuously run since then. The aim has been to set up HCLIM for small domains, using its non-hydrostatic HCLIM-AROME dynamics, and pan-Antarctic runs, using its hydrostatic HCLIM-ALADIN core. This technical work has been done in close collaboration with DMI and MetNO.

As HCLIM has never been used in the Southern Hemisphere before, more effort than expected was needed to debug code, for instance where negative latitudes were explicitly excluded, to detect missing or incorrect input data as their validity for the Southern Hemisphere was never verified, and to evaluate the model performance. The initial progress was also slowed by the ECMWF Data Centre migration to Bologna in autumn 2022, which made essential files and ERA5 boundaries unavailable for months. Finally, it took longer than expected to find a suitable candidate for the PostDoc position that is responsible for this research. Therefore, the planned HCLIM simulations for 2022 has not yet been carried out.

Obviously, this research project is continued in 2023. Since then, significant progress has been made, which is also discussed in the special project progress report of the project "Bipolar regional climate projections".

FIRN MODELLING FOR GREENLAND AND ANTARCTICA

Representing the firn layer evolution of ice sheets

The firn (multi-year snow) layer of ice sheets and glaciers is the surface layer in which accumulated snow gets compressed into ice. The firn layer can be up to 100 m thick in the cold interior of Antarctica. It covers over 99% of the Antarctic Ice Sheet, and about 90% of the GrIS. The firn layer is porous, and as a result, it contains a significant amount of air: up to 30 m^3 per m. This gives allows meltwater to refreeze inside of it. Detailed information of the firn layer is needed to estimate the evolution of this firn air content (FAC), since this is needed to compute the ice sheet's mass loss with radar altimetry data from satellites or to the assess the future stability of ice shelves. For this aim, we model the evolution of the firn layers of the AIS ang GrIS with the firn densification model IMAU-FDM (Brils et al. 2022; Veldhuijsen et al. 2023).

IMAU-FDM is a 1D model running on a single core. As the ECMWF HPCF is in principle not optimized for this kind of task, namely many single core jobs, scripts have been developed to run IMAU-FDM efficiently parallelly in nf and np jobs. As IMAU-FDM is a subsurface model only, it takes surface mass fluxes from RACMO2. Hence, the horizontal spatial resolution of IMAU-FDM simulations is set by the horizontal resolution of the surface data from RACMO2.

In 2021, the model update of IMAU-FDM from versions 1.1G and 1.1A to versions 1.2G and 1.2A and subsequent model evaluation over the periods 1960-2020 and 1979-2020, respectively, has been completed. The updated model description improves the simulation of near-surface temperature, snow surface density, vertical density profiles, and total FAC, compared to observations (e.g. Fig. 4). In 2022, these simulations were kept up to date by extending the simulations until 2021. In addition, to study the model sensitivity to input and parameter uncertainty sensitivity analyses of IMAU-FDM v1.2G and v1.2A have been performed in 2022, which we discuss in more detail below. IMAU-FDM has also been used to perform projections of the evolution of firn layers till 2100 for various emission pathways, also discussed below.

The results of IMAU-FDM for Greenland for 1958-2021 have been put into the perspective of changes in atmospheric circulation over Greenland and associated changes in the North Atlantic Oscillation (NAO) (Brils, Kuipers Munneke, and van den Broeke In revision). We show that the response of the firn thickness is tightly coupled to the atmospheric circulation. For example, in case of a negative NAO state, snow accumulation is reduced along the eastern and south-western sides of the GrIS (Fig. 5), while a positive NAO state only slightly enhances snow accumulation along the eastern coast and has no impact on the snow accumulation in the south-west.

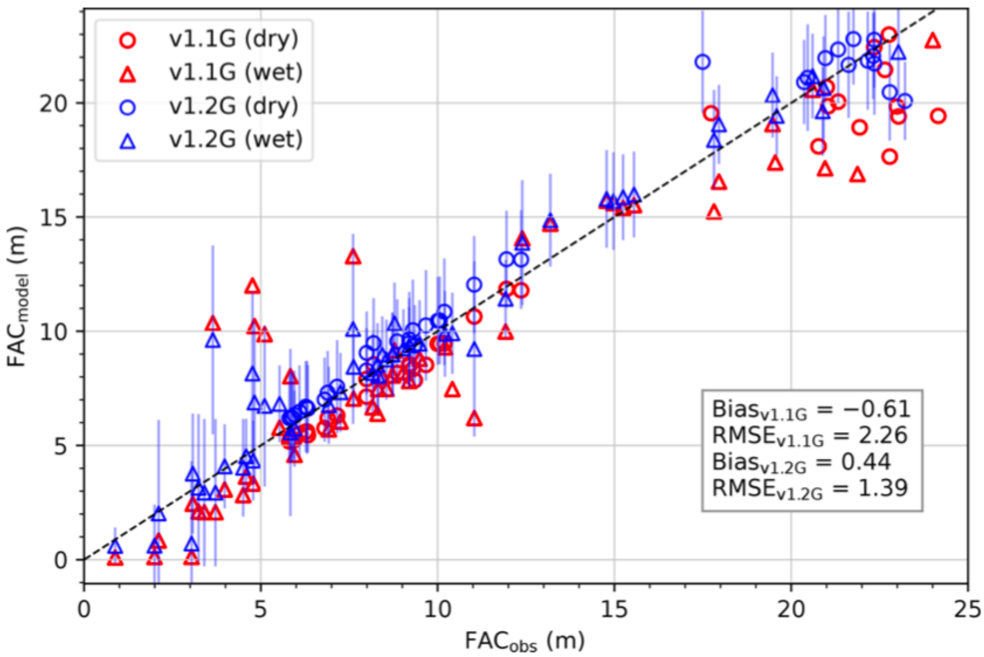

***Figure 4**: Modelled versus observed firn air content in meters for the Greenland Ice Sheet. Dry locations are indicated with circles (melt is less than 5% of annual accumulation), whereas wet locations are indicated with triangles (melt > 5% of annual accumulation). Blue bars indicate uncertainty.*

It is also demonstrated that various parts of the ice sheet respond very differently to changes in the NAO. For example, in the years after 2012, the firn layer over Greenland was able to recover from extraordinary melt in 2012, although in different ways: the southwestern part of the ice sheet experienced decreased surface melt, whereas the east and southeast part received a lot more snowfall. In the north, the firn continued to lose FAC. The analysis also highlighted that, due to the timing of the months with maximum snowfall, firn thickness variations in the southeast part of the ice sheet are large and amplified, whereas on other locations, the seasonal variations are dampened.

FDM projections till 2100 for the Greenland Ice Sheet.

In the future, the firn's ability to retain meltwater may decrease, leading to accelerated sea-level rise. To investigate the possible extent to which the firn will detoriate we performed future simulations for the low and high emission scenarios SSP1-2.6 and SSP5-8.5. The simulations with IMAU-FDM1.2G ran from 1958 to 2100. They were forced with RACMOv2.3p2, which in turn was forced at its boundaries with ERA reanalysis for the period 1958 to 2021 and with CESM for 2021 onwards.

Initial results show a steady decline of the firn's pore space. Unfortunately, we also found that the run contained errors leading to unnatural oscillations in firn thickness. Therefore, these results are not suitable for publication nor further analysis. Furthermore, it has been decided for now not to redo these projections till 2100 and to focus on the analysis of the results from the historic run first. We plan to fix the problem with the future run next year and redo these simulations.

Assessing the uncertainty of Antarctic IMAU-FDM results

To study the model (IMAU-FDM v1.2A) sensitivity to input and parameter uncertainty a sensitivity analysis is performed for 106 locations across the AIS. We tested the model sensitivity to uncertainties in the fresh snow density, the dry-snow densification rate, accumulation forcing,

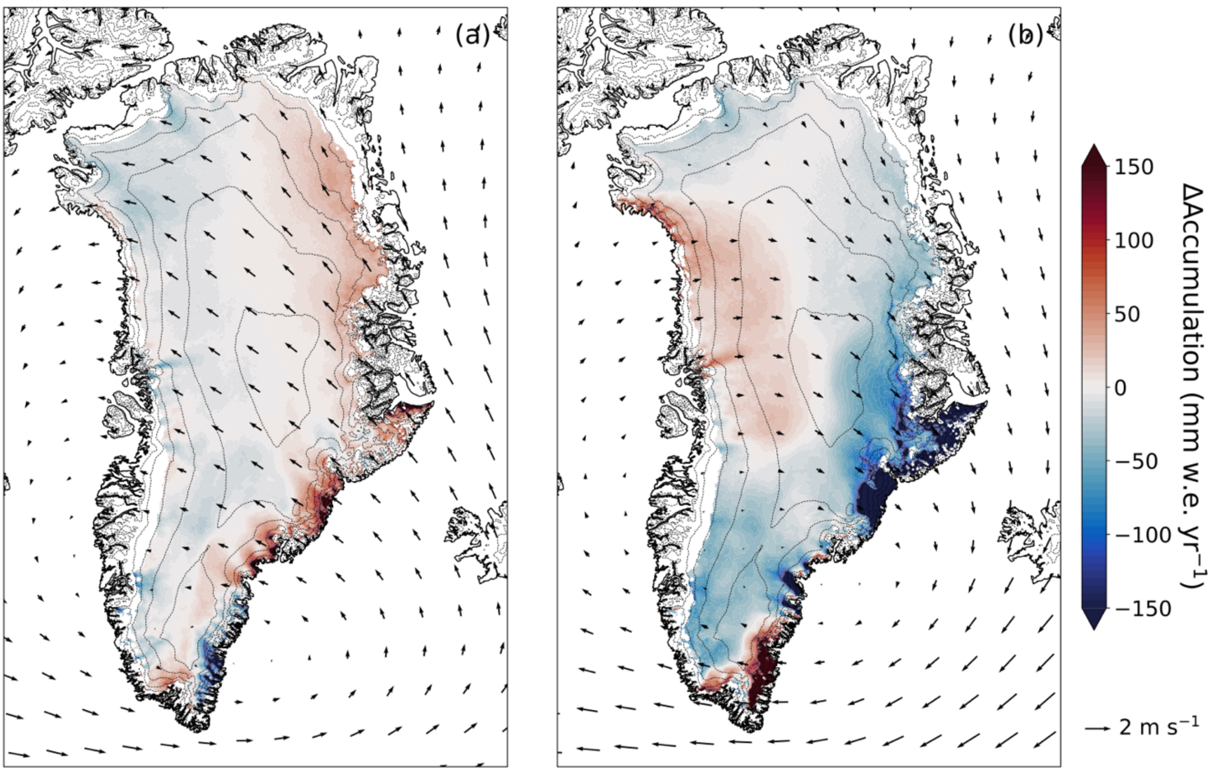

Figure 5: *Mean difference in the annual Greenland Ice Sheet snow accumulation (in mm w.e. per year) and 500 hPa winds between* ***(a)*** *positive and neutral NAO index, and* ***(b)*** *between negative and neutral NAO index.*

temperature forcing and the spin-up procedure. The total uncertainty in firn air content and surface elevation change is shown in Figure 6. We found that the model is most sensitivity to uncertainties in the spin-up procedure in regions with recent climatic changes in precipitation and temperature. These climatic changes results in surface elevation trend differences between IMAU-FDM v1.2A and altimetry measurements. By estimating previous climatic conditions from ice core data, trend differences between can be reduced by 38%. This uncertainty analysis is published in Veldhuijsen et al. (2023).

FDM projections till 2100 for the Antarctic Ice Sheet.

Antarctic wide simulations of the firn evolution till 2100 under various emission pathways using IMAU-FDM v1.2A have been carried out. These simulations are forced by RACMO2.3p2, in turn forced by CESM2, for the scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5. This IMAU-FDM run is mainly used to project future firn air content, the total pore space in the firn, which is a measure of the meltwater buffering capacity of the firn. This is especially important for the Antarctic ice shelves as meltwater saturation and ponding can promote ice shelve disintegration. Figure 7 shows time series of the firn air content for several ice shelves over the period 1950-2100. Ice shelves on the Antarctic Peninsula, the Larsen C, Wilkins and George VI Ice Shelves, will face the onset of firn air depletion already in the coming decades. Most of the other smaller ice shelves, which are more southerly, will only have significant firn air content depletion at the end of the 21st century when the projected global warming exceeds 3 K. Lastly, even in the case severe global warming, the firn air content of the two large Antarctic ice shelves, Ronne-Filchner and Ross, remain relatively stable.

Further analysis, however, showed that IMAU-FDM version 1.2A has significant parametric uncertainty if applied for a transient climate. This uncertainty problem is largely resolved in 2023, and the results presented here are superseded by newer simulations.

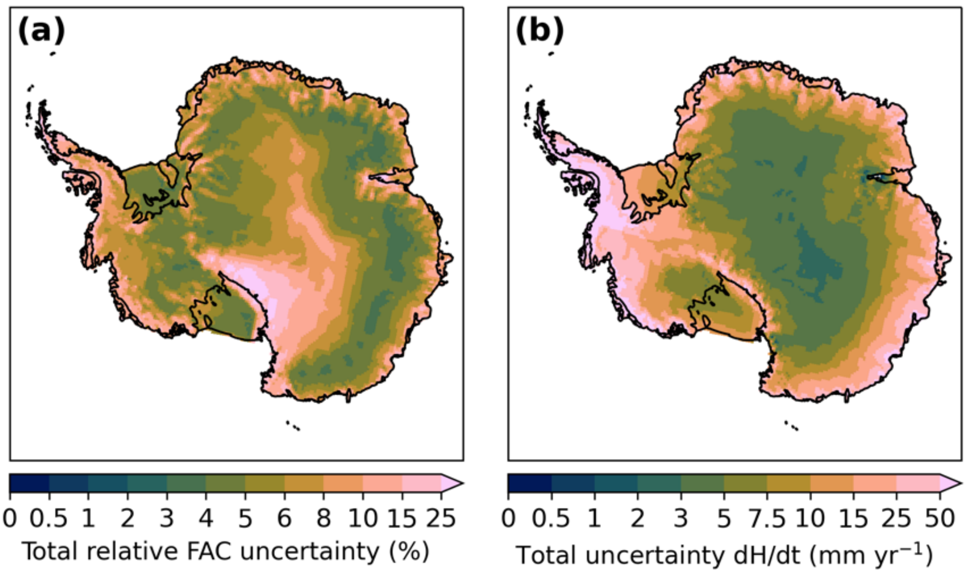

Figure 6: *Ice-sheet-wide total uncertainty in **(a)** firn air content (FAC) over the period 1979-2020 and **(b)** surface elevation change (dH/dt) over the period 2015-2020.*

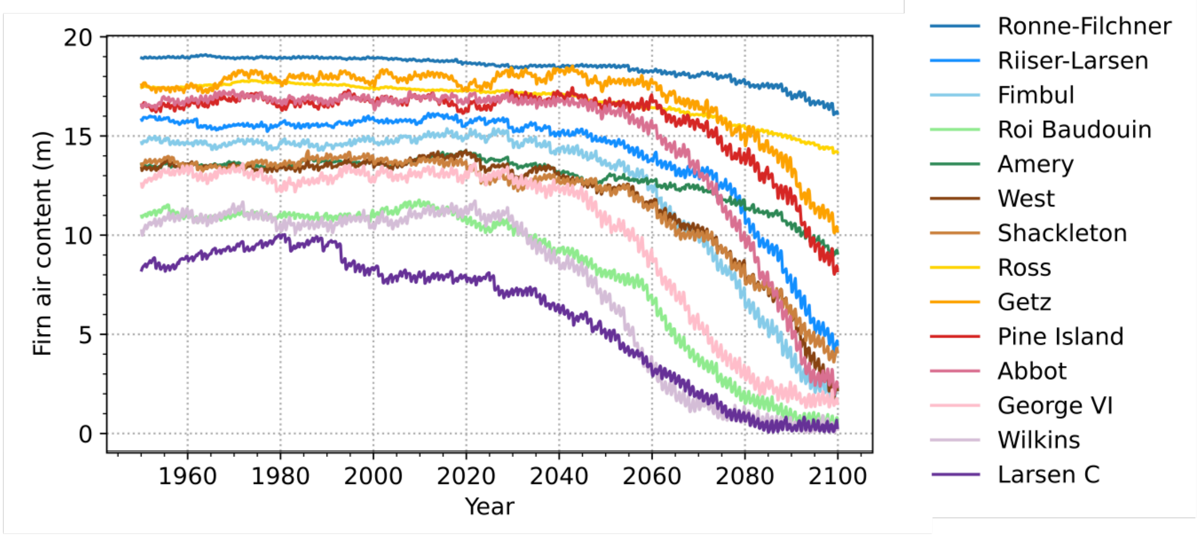

Figure 7: *Time series of simulated average firn air content for several Antarctica ice shelves over the period 1950-2100 under the climate scenario SSP5-8.5, using IMAU-FDM 1.2A.*

List of publications/reports from the project with complete references

Publications since 2022 using RACMO and/or IMAU-FDM, led by members of the research team:

1. Brils, M., P. Kuipers Munneke, W. J. van de Berg, and M. van den Broeke. 2022. 'Improved representation of the contemporary Greenland ice sheet firn layer by IMAU-FDM v1.2G', *Geosci. Model Dev.*, 15: 7121-38.
2. Noël, B., G. Aðalgeirsdóttir, F. Pálsson, B. Wouters, S. Lhermitte, J. Haacker and M. R. van den Broeke. North Atlantic cooling is slowing down mass loss of Icelandic glaciers. Geophysical Research Letters, 49(3): e2021GL095697, 2022. doi: 10.1029/2021GL095697.
3. Noël, B., J. T. M. Lenaerts, W. H. Lipscomb, K. Thayer-Calder and M. R. van den Broeke. Peak refreezing in the Greenland firn layer under future warming scenarios. Nature Communications, 13(6970): 1-10, 2022. doi: 10.1038/s41467-022-34524-x.
4. van Dalum, C., van de Berg, W. J., & van den Broeke, M. (2022). Sensitivity of Antarctic surface climate to a new spectral snow albedo and radiative transfer scheme in RACMO2.3p3. *The Cryosphere*, *16*(3), 1071-1089. https://doi.org/10.5194/tc-16-1071-2022.
5. van den Broeke, M. R., P. Kuipers Munneke, B. Noël, C. Reijmer, P. Smeets, W. J. van de Berg, J. van Wessem. Contrasting current and future surface melt rates on the ice sheets of Greenland and Antarctica: Lessons from in situ observations and climate models. PLOS Climate, 2(5): e0000203, 2023. doi: 10.1371/journal.pclm.0000203.
6. van Tiggelen, M., Smeets, P., Tijm - Reijmer, C., van den Broeke, M., Van As, D., Box, J. E., & Fausto, R. S. (2023). Observed and Parameterized Roughness Lengths for Momentum and Heat Over Rough Ice Surfaces. *Journal of Geophysical Research: Atmospheres*, *128*(2), [e2022JD036970]. https://doi.org/10.1029/2022JD036970.
7. van Wessem, J. M., van den Broeke, M. R., Wouters, B., & Lhermitte, S. (2023). Variable temperature thresholds of melt pond formation on Antarctic ice shelves. *Nature Climate Change*, *13*(2), 161-166. https://doi.org/10.1038/s41558-022-01577-1.
8. Veldhuijsen, S. B. M., W. J. van de Berg, M. Brils, P. Kuipers Munneke, and M. R. van den Broeke. 2023. 'Characteristics of the 1979–2020 Antarctic firn layer simulated with IMAU-FDM v1.2A', *The Cryosphere*, 17: 1675-96.

Other notable publications since 2022 using RACMO and/or IMAU-FDM data:

1. Sasgen, A. Salles, M. Wegmann, B. Wouters, X. Fettweis, B. P. Y. Noël and C. Beck. Arctic glaciers record wavier circumpolar winds. Nature Climate Change, 12: 249-255, 2022. doi: 10.1038/s41558-021-01275-4.

2. S. A. Khan, J. L. Bamber, E. Rignot, V. Helm, A. Aschwanden, D. M. Holland, M. van den Broeke, M. King, B. Noël, M. Truffer, A. Humbert, W. Colgan, S. Vijay, P. Kuipers Munneke. Greenland Mass Trends From Airborne and Satellite Altimetry During 2011–2020. Journal of Geophysical Research: Earth Surface, 127(4): e2021JF006505, 2022. doi: 10.1029/2021JF006505.
3. T. Wei, B. Noël, M. Ding and Q. Yan. Spatiotemporal variations of extreme events in surface mass balance over Greenland during 1958–2019. International Journal of Climatology, 42(15): 8008-8023, 2022. doi: 10.1002/joc.7689.
4. S. A. Khan, W. Colgan, T. A. Neumann, M. R. van den Broeke, K. M. Brunt, B. Noël, J. L. Bamber, J. Hassan, A. A. Bjørk. Accelerating Ice Loss From Peripheral Glaciers in North Greenland. Geophysical Research Letters, 49(12): e2022GL098915, 2022. doi: 10.1029/2022GL098915.
5. J. E. Box, A. Hubbard, D. B. Bahr, W. T. Colgan, X. Fettweis, K. D. Mankoff, A. Wehrlé, B. Noël, M. R. van den Broeke, B. Wouters, A. A. Bjørk and R. S. Fausto. Greenland ice sheet climate disequilibrium and committed sea-level rise. Nature Climate Change, 12: 803-813, 2022. doi: 10.1038/s41558-022-01441-2.
6. B. Huai, M. R. van den Broeke, C. H. Reijmer, B. Noël. A Daily 1-km Resolution Greenland Rainfall Climatology (1958–2020) From Statistical Downscaling of a Regional Atmospheric Climate Model. Journal of Geophysical Research: Atmospheres, 127(17): e2022JD036688, 2022. doi: 10.1029/2022JD036688.
7. A. M. Solgaard, D. Rapp, B. P. Y. Noël, C. S. Hvidberg. Seasonal Patterns of Greenland Ice Velocity From Sentinel-1 SAR Data Linked to Runoff. Geophysical Research Letters, 49(24): e2022GL100343, 2022. doi: 10.1029/2022GL100343.
8. D. Medrzycka, L. Copland and B. Noël. Rapid demise and committed loss of Bowman Glacier, northern Ellesmere Island, Arctic Canada. Journal of Glaciology, 1-14, 2023. doi: 10.1017/jog.2022.119.
9. K. S. Mattingly, J. V. Turton, J. D. Wille, B. Noël, X. Fettweis, A. K. Rennermalm and T. L. Mote. Increasing extreme melt in northeast Greenland linked to foehn winds and atmospheric rivers. Nature Communications, 14(1743): 1-12, 2023. doi: 10.1038/s41467-023-37434-8.
10. T. Wei, S. Zhao, B. Noël, Q.Yan and W. Qi. Deciphering the trend and interannual variability of temperature and precipitation extremes over Greenland during 1958–2019. Journal of Climate, 1-33, 2023. doi: 10.1175/JCLI-D-22-0488.1.
11. The IMBIE Team. Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. Earth System Science Data, 15(4): 1597-1616, 2023. doi: 10.5194/essd-15-1597-2023.

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.)

With the conclusion of the optimizing of RACMO2.4 for the polar regions (please see our progress report for 2023), we will submit ERA5 driven simulations for the Arctic, Antarctic, and high-resolution Greenland domains. After these simulations, RACMO2.4 will be employed to run projections for the Arctic and Antarctic regions within the framework of the EU Horizon 2020 project PolarRES. Albeit these simulations will be commenced in 2023, the motivation, aims and embedding will be discussed in more detail in the Special Project application for 2024.

References

Amory, C. 2020. 'Drifting-snow statistics from multiple-year autonomous measurements in Adélie Land, East Antarctica', *The Cryosphere*, 14: 1713-25.

Brils, M., P. Kuipers Munneke, W. J. van de Berg, and M. van den Broeke. 2022. 'Improved representation of the contemporary Greenland ice sheet firn layer by IMAU-FDM v1.2G', *Geosci. Model Dev.*, 15: 7121-38.

Brils, M., P. Kuipers Munneke, and M. R. van den Broeke. In revision. 'Spatial response of Greenland's firn layer to NAO variability', *Journal of Geophysical Research Earth Surface*.

Déry, Stephen J., and M. K. Yau. 1999. 'A Bulk Blowing Snow Model', *Boundary-Layer Meteorology*, 93: 237-51.

———. 2001. 'Simulation Of Blowing Snow In The Canadian Arctic Using A Double-Moment Model', *Boundary-Layer Meteorology*, 99: 297-316.

Lenaerts, Jan T. M., Michiel R. van den Broeke, Jan M. van Wessem, Willem Jan van de Berg, Erik van Meijgaard, Lambertus H. van Ulft, and Marius Schaefer. 2014. 'Extreme Precipitation and Climate Gradients in Patagonia Revealed by High-Resolution Regional Atmospheric Climate Modeling', *Journal of Climate*, 27: 4607-21.

Noël, B., 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: 2361-77.

Noël, B., J. M. Van Wessem, B. Wouters, L. Trusel, S. Lhermitte, and M. R. van den Broeke. in review. 'Higher Antarctic ice sheet accumulation and melt rates revealed at 2 km resolution.'.

Noël, Brice, Willem Jan van de Berg, Stef Lhermitte, and Michiel R. van den Broeke. 2019. 'Rapid ablation zone expansion amplifies north Greenland mass loss', *Science Advances*, 5: eaaw0123.

Otosaka, I. N., A. Shepherd, E. R. Ivins, N. J. Schlegel, C. Amory, M. R. van den Broeke, M. Horwath, I. Joughin, M. D. King, G. Krinner, S. Nowicki, A. J. Payne, E. Rignot, T. Scambos, K. M. Simon, B. E. Smith, L. S. Sørensen, I. Velicogna, P. L. Whitehouse, G. A, C. Agosta, A. P. Ahlstrøm, A. Blazquez, W. Colgan, M. E. Engdahl, X. Fettweis, R. Forsberg, H. Gallée, A. Gardner, L. Gilbert, N. Gourmelen, A. Groh, B. C. Gunter, C. Harig, V. Helm, S. A. Khan, C. Kittel, H. Konrad, P. L. Langen, B. S. Lecavalier, C. C. Liang, B. D. Loomis, M. McMillan, D. Melini, S. H. Mernild, R. Mottram, J. Mouginot, J. Nilsson, B. Noël, M. E. Pattle, W. R. Peltier, N. Pie, M. Roca, I. Sasgen, H. V. Save, K. W. Seo, B. Scheuchl, E. J. O. Schrama, L. Schröder, S. B. Simonsen, T. Slater, G. Spada, T. C. Sutterley, B. D. Vishwakarma, J. M. van Wessem, D. Wiese, W. van der Wal, and B. Wouters. 2023. 'Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020', *Earth Syst. Sci. Data*, 15: 1597-616.

van de Berg, W. J. 2022. "SPNLBERG progress report 2022." In.

van Tiggelen, Maurice. 2023. 'Roughish ice, snow and turbulent heat fluxes on the Greenland ice sheet', Universiteit Utrecht.

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 Tricht, 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: 1479-98.

Veldhuijsen, S. B. M., W. J. van de Berg, M. Brils, P. Kuipers Munneke, and M. R. van den Broeke. 2023. 'Characteristics of the 1979–2020 Antarctic firn layer simulated with IMAU-FDM v1.2A', *The Cryosphere*, 17: 1675-96.