SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2022
Project Title:	High resolution regional modelling of contemporary and future polar climate and ice sheet surface mass balance
Computer Project Account:	SPNLBERG
Principal Investigator(s):	Dr. Willem Jan van de Berg
Affiliation:	Utrecht University Institute for Marine and Atmospheric Research Utrecht (IMAU)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	None
Start date of the project:	1 January 2022
Expected end date:	31 December 2022

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	30 MSBU	26.7 MSBU	125 MSBU	25.4 MSBU
Data storage capacity	(Gbytes)	200.000	981.660	400.000	1.121.937

Summary of project objectives (10 lines max)

In our research team, we use the regional atmospheric climate models RACMO and HCLIM and the firn (multi-year snow) densification model IMAU-FDM. In the special project proposal, we listed five objectives for 2022:

1. Renewing our operational estimate (1950-2022) at 5.5 km resolution for the Greenland Ice Sheet with RACMO.
2. Creating a new operational estimate (1979-2022) at 11 km resolution for the Antarctic Ice Sheet with RACMO.
3. Performing a simulation of the Arctic climate (1950-2022) at 11 km resolution with RACMO.
4. Test HCLIM, extended with the sea ice module SICE, for a region in West Antarctica at 2 to 2.5 km resolution.
5. Carry out detailed projections of the contemporary and future evolution of the firn layer of the two ice sheets during the 20^{th} and 21^{st} century using IMAU-FDM.

Summary of problems encountered (10 lines max)

During the first half of 2022, two problems have been encountered.
Objectives 1 to 3 are planned to be carried out by RACMO2.4, a new version of RACMO. The development of this version appeared to be more work than expected. Subsequently, we have not started these simulations yet. It is foreseen that these simulations are still being carried out during 2022, either by using RACMO2.4 or by reverting to the operational but older version of RACMO.
Objective 4, testing HCLIM, will be carried out by a new Postdoc. The recruitment took longer than expected. The selected candidate will start on 15 August and we will commerce these simulations shortly thereafter.

Summary of plans for the continuation of the project (10 lines max)
List of publications/reports from the project with complete references

For the remainder of 2022, we have the following plans:

a) Once we have approved RACMO2.4 for usage, we will first run RACMO2.4 for Antarctica (Objective 2) and subsequently the Arctic and Greenland (Objectives 1 and 3).
b) If the release of RACMO2.4 faces more delays, we will use a slightly updated version of the currently operational version for the Arctic and Antarctica (Objectives 2 and 3).
c) Performing test simulations with HCLIM for West Antarctica (Objective 4) and start final simulations if possible.
d) Continue with producing firn layer evolution projections for both ice sheets.
e) Complete the various model development projects.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

Summary of results

The research of our team at Utrecht University focusses on polar regions, thus Antarctica and Greenland with excursions to glaciated regions like on Iceland and Patagonia. We are interested in the local climate, as well as the surface mass balance (SMB) of the glaciated areas. The SMB is the net accumulation or surface mass loss due to the combined processes of snowfall, evaporation, snowmelt, meltwater retention and meltwater runoff. Furthermore, we are interested in the evolution of the firn layer covering most of the surface of glaciers, ice caps and ice sheets. Where the net annual SMB is positive, snow keeps accumulating, building up this firn (multiyear snow) layer, in which fresh snow gradually get compressed to glacial ice. Our results contribute, for example, to the understanding of the current global mean sea level rise (GMSLR), and to the projections of GMSLR.

The research progress in 2022, facilitated by the SPNLBERG special project can be summarized as follows:

RACMO – model simulations

Operational estimates

In 2022, we kept up to date our operational estimates (abbreviated as RACMO2.3p2-ERA5 simulations) of the climate and surface mass balance for Antarctica at 27 km resolution, and for Greenland and surrounding regions at 5.5 km resolution. Both simulations use RACMO version 2.3p2 (RACMO2.3p2) and are driven by ERA5 at its lateral boundaries and now extend till April 2022. The modelled SMB from the simulation covering Greenland is subsequently statistically downscaled to products on 1 km resolution over Greenland and 500 m resolution over Iceland, which is also included in the model domain for Greenland.

The data set for Greenland is an extension of our work published in Noël et al. (2019) and is essential for our international collaborators to update their operational products: e.g., estimates of ice sheet mass balance (Mouginot et al., 2019; The IMBIE team, 2019; King et al., 2020; Mankoff et al., 2021) and runoff discharge (Mankoff et al., 2020). The data set for Antarctica has been similarly used internationally to assess the ice sheet mass balance, e.g., IMBIE team (2018), and we will continue to participate in the ice sheet mass balance assessments of the IMBIE collaboration (see imbie.org).

The data set for Iceland is novel. A paper discussing this data set (Noël et al., 2022) has been published this year. In this study, the future SMB of the Icelandic glacier is also estimated (Fig. 1). For this estimate, data from RACMO simulations driven by CESM2 (RACMO2.3p2-CESM2) have been used. These simulations have been carried out at ECMWF in 2019 and 2021.

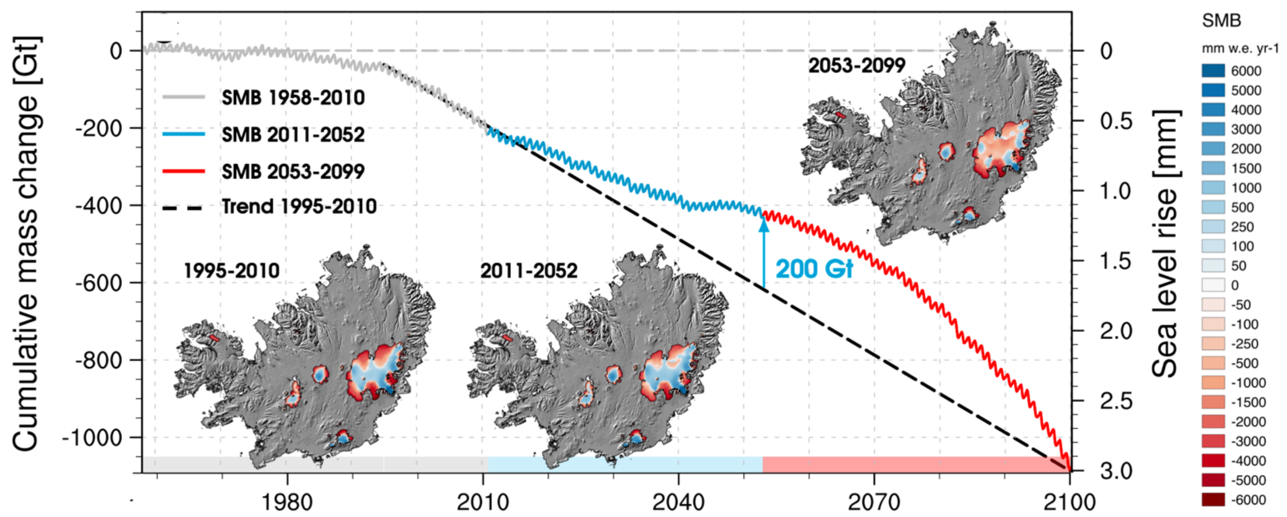

Figure 1: Time series of monthly cumulative glacier-integrated mass change from 1958 to 2099 under a high-end warming scenario (SSP5-8.5). Three mass balance stages are distinguished: 1958-2010 (grey), 2011-2052 (cyan) and 2053-2099 (red). Coloured bands highlight the three stages. The dashed black line extrapolates the 1995-2010 mass loss trend until 2099. Mass loss is converted into mm sea level rise equivalent (right axis). Inset maps represent SMB of Icelandic glaciers averaged for 1995-2010, 2011-2052 and 2053-2099.

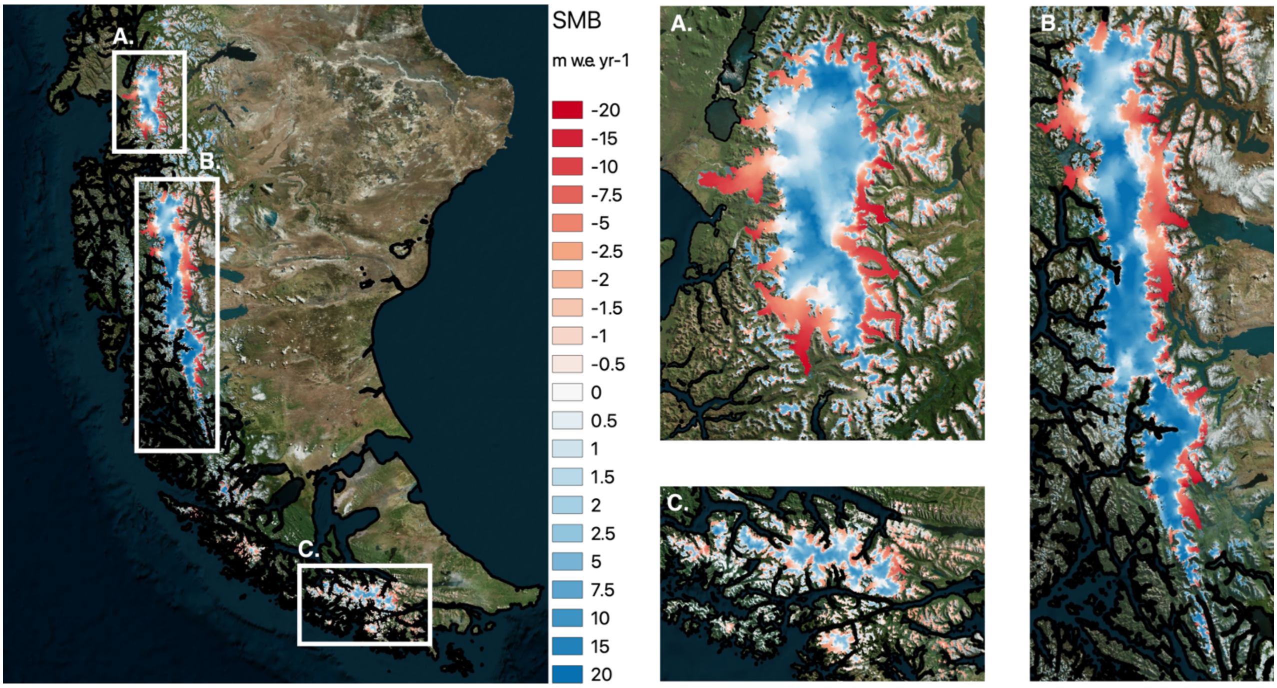

Figure 2: *SMB maps of the Patagonian ice fields as modelled by RACMO2.3p2-ERA5 at 5.5 km, statistically downscaled to 500 m spatial resolution. Insets A., B., and C. zoom in on three ice fields of interests.*

We also carried out a new, present-day (1979-2021) simulation for Patagonia using RACMO, version 2.3p2, at 5.5 km resolution, forced by ERA5. The focus of this simulation is on the Patagonian ice fields. The modelled SMBs are further statistically downscaled to 500 m resolution (see Fig. 2). The data set will be the core of a forthcoming publication investigating the drivers of recent mass loss in Patagonia. Since this area is poorly represented in the literature, with little amount of spatially continuous, high-resolution SMB data sets, we anticipate that the product will raise broad interest in the mountain glacier community.

RACMO – model development

In 2022, model development on RACMO focussed on three topics: the representation of snowdrift, the surface roughness of glacial ice and a general update of RACMO.

Snow drift

A blowing snow model has been implemented in RACMO in the previous years and has been subsequently used for projections of blowing snow in both Antarctic and Greenland Ice Sheets. However, the model failed when compared to the recent observations from East Antarctica (Amory, 2020). To fix the problem, the blowing snow model PIEKTUK (Déry and Yau, 1999) in RACMO was updated.

The following modifications were done:

a) Previously, only limited ice particle size distribution classes were being considered keeping computational expenses in mind. Therefore, ice particles with sizes up to 50 μm were only considered in the calculations. However, this was found to be unsatisfactory. To overcome this the ice particle size distribution class was made non-uniform to cover all ice particles with sizes varying between 2 and 300 μm.

b) The saltation model was updated. This model describes the relation between the near surface wind speed, surface properties and the particle concentration in the first couple of centimetres above the surface.

c) Previously, the single column snow drift model assumed log-law varying velocity and humidity profiles, ignoring the thermal stratification. Hence, it made no use of the velocity, temperature, and humidity profiles of RACMO. The update removes this assumption, and RACMO profiles are now passed on from RACMO to PIEKTUK and interpolated to the PIEKTUK model levels.

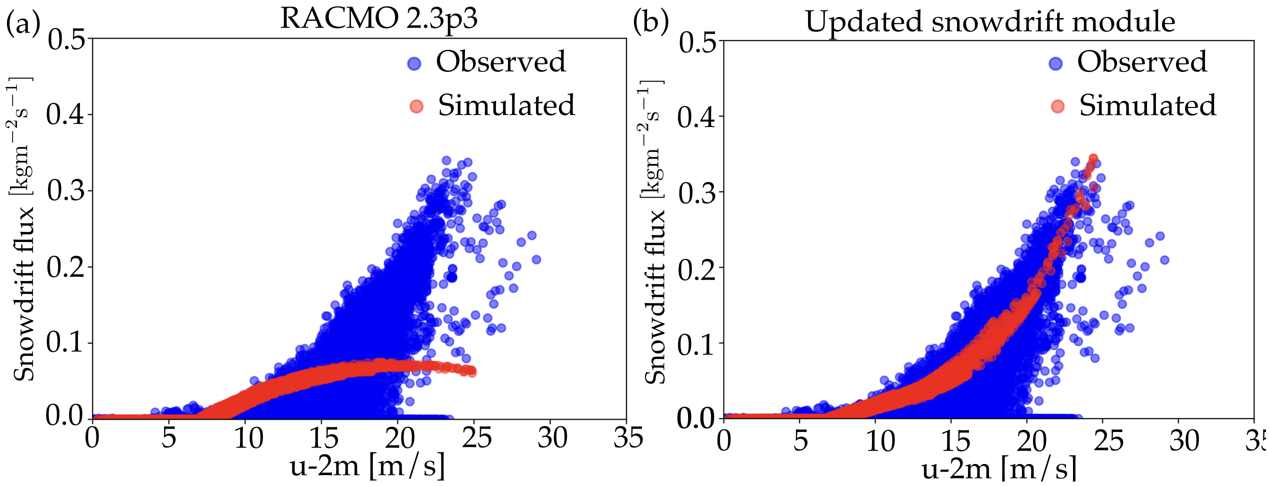

Figure 3*: Drifting snow mass flux versus 2 m wind speed at site D47 in East Antarctica. Results produced with (a) RACMO 2.3p3 and (b) the offline updated snowdrift module.*

d) In the previous version, the moisture and heat flux from blowing snow sublimation was added to the surface energy and moisture balance. However, additional analyses showed that most of the snow drift sublimation occurs between 10 and 300 m above the surface. In the updated version, blowing snow sublimation changes the temperature and humidity of the associated RACMO levels, which improves the representation of impact of snow drift on the katabatic boundary layer.

To validate the updated model, RACMO2.3p3 runs were done to obtain the velocity, temperature, and humidity profiles for the years 2011 and 2012. The velocity profiles from the climate runs were used as the input to tune the snowdrift model offline. The results from the model were compared to the observations from East Antarctica (Amory, 2020). Specifically, average blowing snow fluxes below 2 m height above the ground was compared with the observations. Figure 3 shows a comparison between the blowing snow predictions from RACMO2.3p3 and the updated blowing snow model. The results from the 1D model matches much better than the previous version when compared to the observations, although the observed large scatter in observations is not yet represented as the updated results are from 1D model using sampled velocities.

The next step is to implement the improvements of the offline model into the snow drift model in RACMO and evaluate the online modelled snow drift against the observations.

Surface roughness parameterization

In the current versions of RACMO, two different but fixed values are used for the surface roughness of snow covered and bare ice surface of glaciated regions. For bare ice surfaces, this is deemed insufficient as the surface roughness varies greatly due to melt formed hummocks or ice flow formed surface fracturing. To test the impact of spatial and temporally varying surface roughness estimates for bare ice, seven RACMO2.3p2 simulations have been performed for the Greenland ice sheet on 5.5 km resolution. These simulations all cover 2016-2021 and use different parameterizations for the surface roughness lengths over the ice sheet.

First results indicate that modelled surface melt is mostly sensitive to changing the roughness length for heat (z_{0h}), especially when a large value for roughness length for momentum (z_{0m}) is used (Fig. 4). Knowing that the low-lying ice regions on the Greenland ice sheet are very rough, we expect that improving the surface roughness has a significant impact on modelled surface runoff.

In the remainder of 2022, three more simulations will be run with a parameterized z_{0m} of ice using a new model (Van Tiggelen et al, in review), and compare the final output to a unique dataset of in situ weather station observations. In addition, ICESat-2 data will be processed across the entire Greenland Ice Sheet to make a new map of surface roughness. The methods have already been tested and published using a different supercomputer for a smaller area, which has revealed to be very promising.

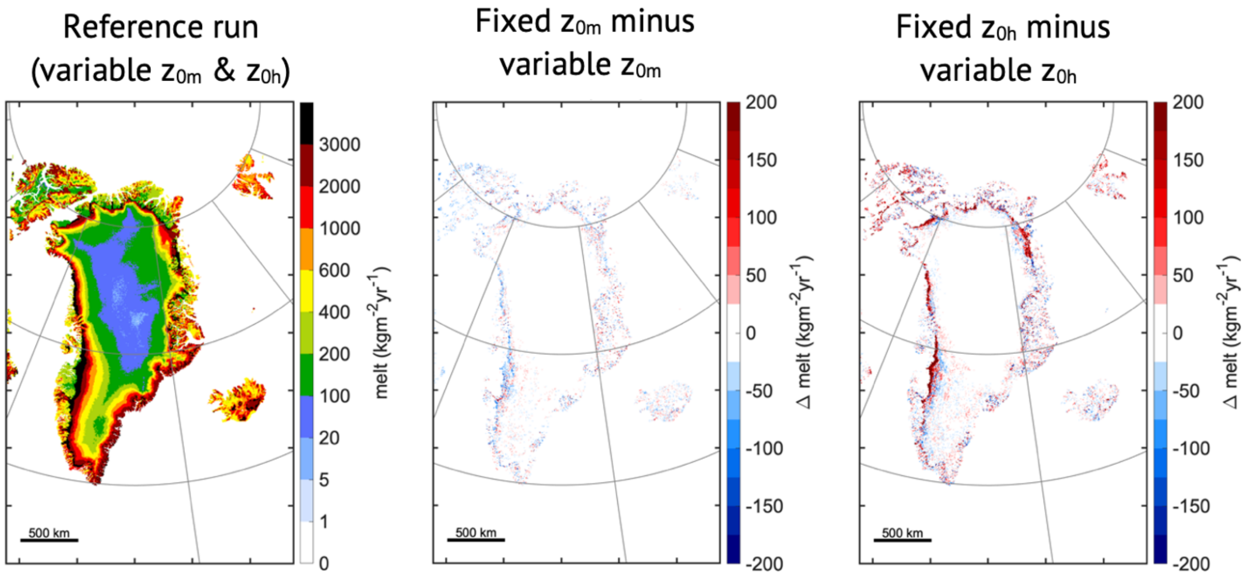

***Figure 4**: Modelled surface melt during 2019 using the reference simulation (left), difference in surface melt when implementing a variable surface ice roughness length (z_{0m}) (middle), difference in surface melt when using a fixed roughness length for heat (z_{0h}) (right)*

General update of RACMO

In 2021, we commenced with the development of a fully new RACMO version, RACMO2.4. RACMO consists of the dynamical core of the limited area model HIRLAM and the parameterizations of physical processes as in ECMWF IFS physics packages, complemented with in-house developed code to represent glaciated surfaces better. The core of this general update is updating the physics package from the ECMWF IFS cycle Cy33r1 to Cy47r1. Between the two IFS code versions, major improvements have been made by the ECMWF in the cloud, turbulence, radiation, surface, and convection schemes.

During 2021, the development of RACMO was almost exclusively limited to coding. In 2022, the development of RACMO2.4 continued, and first tests have been carried out, providing promising results. It is expected that on the course of 2022, RACMO2.4 becomes available for the planned simulations for 2022. In the case that RACMO2.4 provides a far poorer description of the polar climate than the current operational version of RACMO, we will revert to this older version for these planned simulations, while continuing to improve the representation of the polar climate by RACMO2.4.

Firn modelling work with IMAU-FDM

IMAU-FDM is a 1D lagrangian model that represents the evolution of the firn layer because of accumulation, melt, refreezing, and compaction. It is driven at the surface by mass fluxes, e.g., accumulation, evaporation and snow melt and the skin temperature of the snow.

Development & estimates for the recent past

By incidence, systematic differences between the firn model state were found if the model was run using implicit and explicit time stepping. This difference became apparent at the blending zone between dry firn regions, for which implicit time stepping was used, and the (occasionally) wet firn regions, for which explicit time stepping was used. It took some time before the root cause of these differences was found. Once localized and corrected, we decided to use from now on implicit time stepping only albeit with a shorter time step then before.
After correcting this model error, it was necessary to rerun our RACMO2.3p2-ERA5 driven simulations estimating the firn evolution of the recent past, thus 1957-2022 for Greenland and 1979-2022 for Antarctica.

Projections for Antarctica

Continuing the research project started in 2021, we performed a future IMAU-FDM Antarctic wide simulation covering the period 1950-2100 at a 27 km resolution under the SSP5-8.5 climate change scenario. This IMAU-FDM simulation is driven by the RACMO2.3p2-CESM2 simulation carried out at ECMWF in 2019.

In the SSP5-8.5 scenario, surface melt and densification rates are expected to increase over Antarctica. Enhanced surface melt will lead to firn air content depletion and increased firn saturation. On the other hand, enhanced snowfall will add additional pore space to the firn. This IMAU-FDM run is used to project future firn air content, which is especially important for the Antarctic ice shelves as firn air content depletion promotes ice shelve disintegration. Figure 5 shows the decrease in average firn air content under the SSP5-8.5 scenario for several ice shelves using this CESM2 projection. 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 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.

The next steps are to use an updated version of IMAU-FDM which allows for simulation branching and to run IMAU-FDM using RACMO2-CESM2 projections under the SSP1-2.6 and SSP2-4.5 scenarios and to inquire better the model uncertainties in the projections.

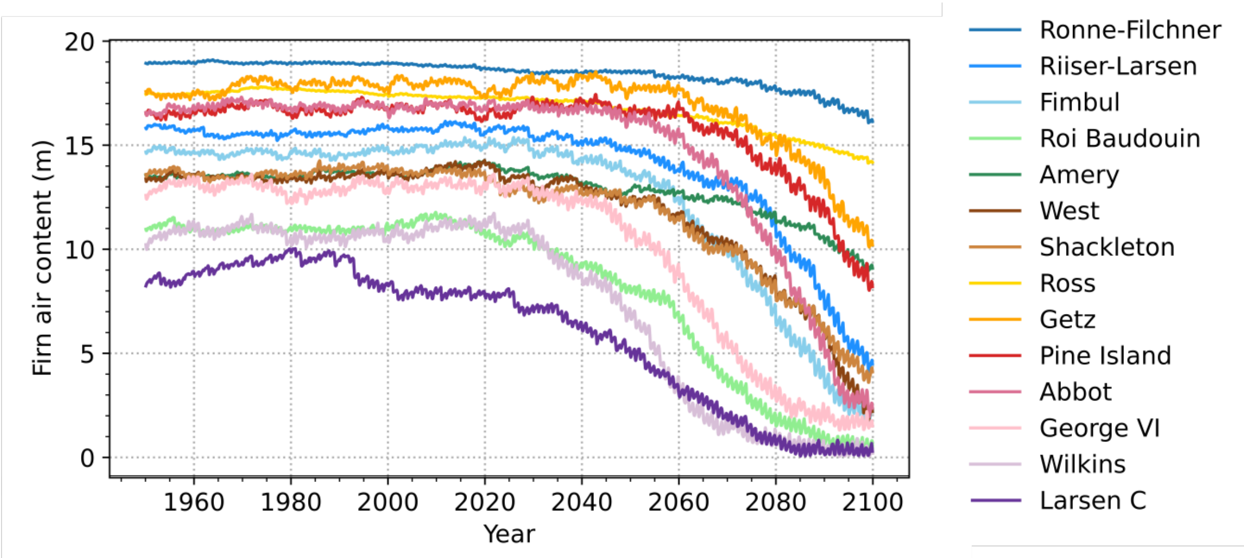

Figure 5*: Time series of simulated average firn air content for several Antarctica ice shelves over the period 1950-2100.*

Approximate breakdown of used HPCF resources

Task	Approximated SBU usage (in million SBUs)
RACMO2.3p2, present day simulations	9.9
RACMO development on snow drift	1.2
RACMO development on surface roughness	9.1
RACMO upgrade to IFS CY47R1	0.7
IMAU-FDM, present day estimates update	3.5
IMAU-FDM, projections for Antarctica	1.0
SUM	25.4

References

SPNLBERG team members and supervisors in bold.

Amory, C., Drifting-snow statistics from multiple-year autonomous measurements in Adélie Land, East Antarctica, The Cryosphere, 2020, https://doi.org/10.5194/tc-14-1713-2020.

Déry, S. J., and M. K. Yau, A bulk blowing snow model, Boundary-Layer Meteorology, 93, 237-251, 1999. https://doi.org/10.1023/A:1002065615856

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.

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.

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.

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.

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.

Noël, B., Aðalgeirsdóttir, G., Pálsson, F., Wouters, B., Lhermitte, S., Haacker, J. M., & **van den Broeke, M. R.** (2022). North Atlantic cooling is slowing down mass loss of Icelandic glaciers. Geophysical Research Letters, 49, e2021GL095697. Doi: 10.1029/2021GL095697

The IMBIE team, including **M. R. van den Broeke, B. Noël, W. J. van de Berg** and **J. M. van Wessem**, Mass balance of the Antarctic Ice Sheet from 1992 to 2017, Nature, 2018, doi: 10.1038/s41586-018-0179-y.

The IMBIE Team, including **M. R. van den Broeke, B. Noël, W. J. van de Berg** and **J. M. van Wessem,** Mass balance of the Greenland Ice Sheet from 1992 to 2018, Nature, 2019. doi : 10.1038/s41586-019-1855-2.

Van Tiggelen, M., P. C. J. P. Smeets, **C. H. Reijmer, M. R. van den Broeke**, D. van As, J. E. Box, and R. S. Fausto, Parameterization of roughness lengths for momentum and heat over rough snow and ice surface. J Geophys Res Atmos, in review.