SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Bipolar regional climate projections
Computer Project Account:	spnlberg
Start Year - End Year :	2023 - 2023
Principal Investigator(s)	Dr. Willem Jan van de Berg
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The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The overarching objective of the SPNLBERG project is to facilitate the research using the (polar adapted) regional climate models RACMO and HCLIM, and the firn densification model IMAU-FDM. This research aims to improve our understanding of the climate and surface mass balance, thus net accumulation or ablation, of the Greenland and Antarctic Ice Sheets; provide detailed estimates of the recent historic climate, and projections until 2100. Furthermore, additional calculations are carried out to model the evolution of the firn layer in more detail.
In 2023, the focus of the work carried out with the SPNLBERG budget pointed towards 1) completing the model development of RACMO, version 2.4p1, and enabling HCLIM to simulate well Antarctic domains; 2) Renewing operational historic simulations of RACMO for the Arctic, Greenland and Antarctica; 3) Adapting the firn densification model for transient simulations; and derive those simulations until 2100 for the Antarctica Ice Sheet.

Summary of problems encountered

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

Progress was less than expected in 2023 for two main reasons. It took longer than expected in 2022 to finalize the code development and model tuning of RACMO version 2.4p1. This caused some delays, which were further enlarged by unexpected personnel changes. A Postdoc left our group for a permanent position, and it took some time to hire an adequate replacing new Postdoc. Similarly, it took more effort than expected to adapt HCLIM to work properly for Southern Hemisphere domains, and long simulations were affected by bugs that inhibited simulations to be suitable for publication or any other way of dissemination. Similarly, transient future simulations with the firn densification model were carried out for Antarctica but not for Greenland: model development was given priority over performing longer runs.

Experience with the Special Project framework

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

This framework works smoothly, and the ECMWF supercomputer is reliable and fast. With the growing size of output, retrieving large amounts of archived data from ECFS is sometimes cumbersome. Efficient scripts and retrieval methods help, nonetheless retrieving data takes time.

The only potential complicated aspect of the Special Project framework is the late announcement of the granting of the budget. Granting, or denial, is announced in December. If our proposal would be denied, it would leave us with very little time to arrange alternative computational facilities. This would be very problematic, as the ECMWF special project budgets are essential to carry out our research.

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.)

Overview

In 2023, our research group used the SPNLBERG budget to run the regional climate models RACMO and HCLIM, and various versions of the firn densification model IMAU-FDM. Below, the main simulations of each model are discussed, if not already discussed in the 2023 progress report.

RACMO

RACMO is a hydrostatic regional climate model, initially developed by KNMI. It consists of the dynamical core of the regional climate model HIRLAM and IFS physics. At IMAU, we developed a polar version of RACMO, with additional descriptions of surface and boundary layer processes that are essential to represent the atmosphere-soil interaction over glaciers, ice caps and ice sheets. These additions include an extra surface tile representing a glaciated surface where a thick layer of ice disconnects the atmosphere from the bedrock, and at most places a thick multi-year snow layer disconnects also this glacial ice from the atmosphere. For this tile, a multi-layer snow-ice model is implemented, which captures the impact of heat diffusion, radiation penetration, snow densification, surface and internal melt, meltwater percolation, retention, refreezing and runoff of the surface-atmosphere mass and energy fluxes, as well as the overall surface mass balance of this glaciated tile. Furthermore, boundary layer processes like snow drift and the subsequent snow transport and snow sublimation are implemented.

In 2023, we used two versions of RACMO, namely versions 2.3p2 and 2.4p1. Version 2.3p2 is based on IFS cycle 33r1. Version 2.4p1 is based on IFS cycle 47r1 and has furthermore numerous updates in the description of glacial processes, like a new snow/ice albedo scheme that includes radiation penetration, an updated snow drift model, and an updated tundra snow model.

We primarily run RACMO over the Greenland and Antarctic Ice Sheets. Besides that, we also carry out, on irregular basis, dedicated simulations for other glaciated regions, like Patagonia. There are two types of simulations: simulations driven by ECMWF analyses, where we create hindcast of the historical climate, and simulations driven by Earth System Model (ESM) atmospheric data, which provide detailed projections till 2100 or further. All simulations are carried out as linear simulations due to the long memory effects in firn.

These simulations are firstly used to improve our understanding of the climate and (sub)surface process of Greenland and Antarctica. Furthermore, these simulations provide detailed and thoroughly evaluated estimates of the glacial surface mass balance - local accumulation or removal of mass at the glacier surface - required to estimate the overall mass balance of the Greenland and Antarctic Ice Sheet. These ice sheet mass balance estimates are updated twice a year. Therefore, our operational simulations need to be extended every half year. Lastly, our model data are used in numerous other research projects, e.g., to as surface boundary forcing of ice sheet models.

Below, we discuss the main RACMO simulations carried out in 2023.

ERA5 driven simulation of Greenland using version 2.3p2 (40 million SBU)

The primary operational simulation for the Greenland Ice Sheet is on 5.5 km resolution. Before the current ATOS High Performance Computing Facility (HPCF) became available, a multi decadal simulation on this domain put a considerable claim on computational budgets, even though Greenland is considerably smaller than Antarctica. When ERA5 was created as successor of ERA-Interim, the years preceding 1979 were not available initially. Therefore, we decided in 2020 to renew our operational simulations for Greenland from 1990 onwards only. As a result, our operational simulation started in 1957 with ERA-40 boundaries, uses ERA-Interim boundaries for 1979-1989 and ERA5 boundaries afterwards.

Such mixed-boundary simulation is hard to compared to a newer simulation with RACMO that uses ERA5 boundaries only. Therefore, we decided it was worth the effort to rerun RACMO version 2.3p2 with ERA5 for 1940 to 2022. Furthermore, the surface mass balance fields of the glaciated regions of Greenland are further statistically downscaled to a 500 m resolution.

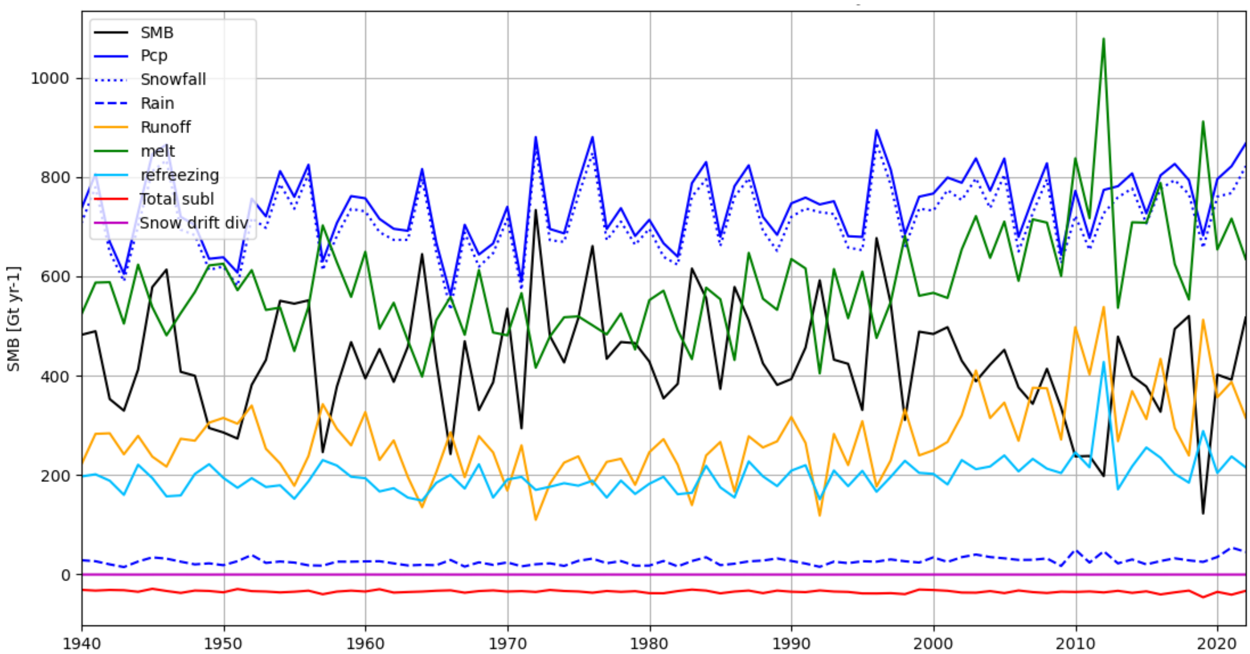

Figure 1: *Timeseries of the surface mass balance (SMB) and its components of the Greenland Ice Sheet from the ERA5 driven RACMO2.3p2 simulation. Pcp denotes total precipitation; total sublimation includes both surface and snow drift sublimation.*

Figure 1 shows the annual surface mass balance (SMB) integrated for the Greenland Ice Sheet and the glaciers and ice caps of Greenland. The data shown in Figure 1 are the results from RACMO prior statistical downscaling to 500 m resolution. Compared to the 1960-1990 period, in which the Greenland Ice Sheet was close to equilibrium, melt and runoff were slightly higher in the period 1940-1959. In this period, the enhanced runoff is mostly balanced by higher precipitation, leading to an insignificant change in the SMB. In contrast, melt and runoff increased considerably since 1990, and only in some years this additional mass loss can be compensated by the higher precipitation.

ERA5 driven simulation of Patagonia using version 2.3p2 (18 million SBU)

In the beginning of 2023, we also carried out a ERA5 driven RACMO simulation for Patagonia. This simulation was carried out on 5.5 km resolution. The surface mass balance fields of glaciated area were further statistically downscale to a resolution of 500 m. This simulation is discussed in the 2023 SPNLBERG progress report.

Model development (30 million SBU)

In 2023, a considerable amount of research time and computer resources have been spent to finalize the development of RACMO version 2.4p1. The numerous upgrades in the IFS physics description led to considerable changes in the modelled climate and precipitation patterns over Greenland and Antarctica. Especially the interaction between the new cloud scheme, which allows for advection of hydrometeors, led to enhanced precipitation for many regions of Greenland. Subsequently, as the winter snow accumulation needs to be melted before ice ablation starts, and snow absorbs less sunlight (thus heat) than ice, this enhanced precipitation reduced also the summer ablation. As a result, the first results for Greenland with the updated IFS physics were considerably deviating from the expected range based on various observational techniques. Therefore, a considerable number of short simulations were carried out to find the best suitable and still realistic parameter settings for our polar applications of RACMO.

This new version of RACMO, 2.4p1, is described in detail in van Dalum et al. (2024). This paper also provides some first results for the new CORDEX domain for Antarctica (11 km resolution) and for Greenland. Furthermore, it discussed results for the updated Arctic CORDEX domain, a model domain that was not employed for version 2.3p2.

Besides the already mentioned updates in the cloud scheme, version 2.4p1 introduces a five-layer snow scheme over non-glaciated land. This scheme is embedded in the IFS code, but not active for normal weather forecasts applications. For our purposes, this multi-layer snow scheme allows to represent the seasonal evolution of snow over the Arctic regions faithfully, as shown in Figure 2. In general, the biases in the modelled snow depth are small, except for more mountainous regions like Western Scandinavia and the West coast of Canada and Alaska. This overestimated snow depth could be due to overestimated precipitation over mountains, or missing snow removal processes like snow drift. This needs to be assessed in further research.

Updated snowdrift parameterization (18 mSBU)

Parallel to the development of RACMO2.4p1, a vigorous update of the snowdrift scheme in RACMO was carried out. This update was necessary as new observations in Antarctica (Amory, 2020) showed that the original snowdrift code completely misrepresented the relation between surface wind speed and snow drift fluxes, which is the basic property and primary observable property of snow drift.

Some of the model code development and induced improvements on the representation of the Antarctic surface climate is described in the SPNLBERG final report of 2022. In 2023, a paper on this model improvement has been drafted and submitted, and during this process some more simulations were needed. This paper, Gadde and van de Berg (2024), is currently in review. All updates presented in this paper are adopted in the new RACMO version 2.4p1, discussed above.

ERA5 driven historical simulation for Antarctica using version 2.4p1 (37 mSBU)

After completion of the tuning for version 2.4p1, we launched a long historical, ERA5 driven, simulation what will be our new operational product for Antarctica. It employs the new CORDEX domain, which is slightly larger and rotated compared to its predecessor. The new run is on 11 km resolution, or to be precise, 0.1 degree on a rotated latitude-longitude grid. The simulation starts, after about 5 years of spin-up, in 1960. Initially it was run till the end of 2022; in the spring of 2024 we added the year 2023. We chose to start the simulation in 1960 as we received indications that the ERA5 boundaries were reliable prior 1979, so prior the start of satellite remote sensed atmospheric humidity. Analysis of the model output nonetheless revealed a clear stepwise increase in precipitation over East Antarctica in 1979, which largely limits the value of the results prior 1979.

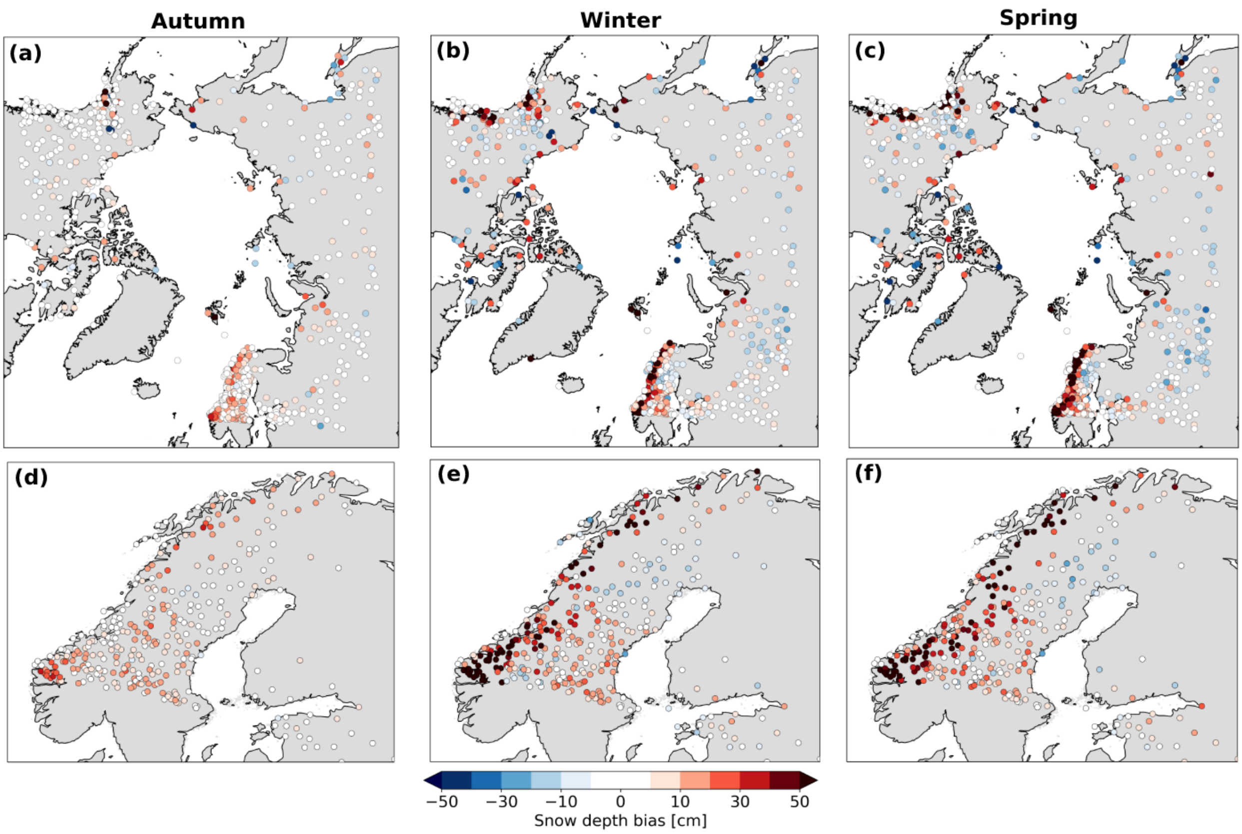

***Figure 2:** Mean snow depth bias of RACMO2.4p1 with respect to daily in-situ observations for 2002-2003 for autumn (a), winter (b) and spring (c). Scandinavia is shown separately in (d)-(f). Red denotes an overestimated snow depth in RACMO2.4p1.*

The results of this simulation have been analyzed, and a publication, focusing on the surface mass balance and near surface climate of Antarctica is in draft. The evaluations show that the new simulation agrees well with observations. Figure 3 shows, for example, the 2-m temperature (T2m) of RACMO2.4p1 compared to in-situ observations that are scattered around the Antarctic ice sheet that are part of the AntAWS data set. The figure illustrates that the temperature is modeled well in RACMO2.4 with respect to the large number of observations available (N = 888899), with only a small cold bias present in RACMO2.4p1.

ERA5 driven simulation for the Arctic using version 2.4p1 (18 mSBU)

Within the framework of PolarRES and Arctic CORDEX, we carried out a 11 km ERA5 driven simulation for 1980-2022. Figure 4 shows the annual mean precipitation. It shows the known patterns, for example, a dry central Arctic Ocean and Northern Greenland. Elevated ranges, like the Ural Mountains, receive more precipitation than the surrounding area's. Mountain ranges along the ocean are modelled to receive the highest precipitation amounts, the Norwegian coast and Southern coast of Greenland receive 2 m of precipitation per year, with extremes up to 4 m. The West coast of Alaska and Canada receives even higher precipitation amounts, locally up to 5-8 m per year. As an earlier test run (Fig 2.) showed that seasonal snow depths were overestimated in mountainous regions, more evaluation is needed before can be concluded that these modelled precipitation values are realistic.

This simulation serves as reference for the ESM driven projections (1980-2100, SSP3-7.0) that are run in 2024. Furthermore, it will be used to compare with results from other RCMs and ESMs within the PolarRES project. Here, the overall mean climate will be analyzed, but also societal impacting synoptic situations like occurrence frequencies of rain on snow or snow-free frozen ground events.

ERA5 driven simulation for Greenland using version 2.4p1 (10 mSBU)

In 2024, we started also the last of our three main ERA5 driven simulations, namely the on for Greenland at 5.5 km resolution. This simulation started in 1945, preceded with a spin-up using the 1940-1944 data. This simulation will become our new operational dataset for the GrIS. At the end of 2023, this simulation was halfway, it is completed in 2024. We will, therefore, discuss the results of this simulation in the 2024 progress report.

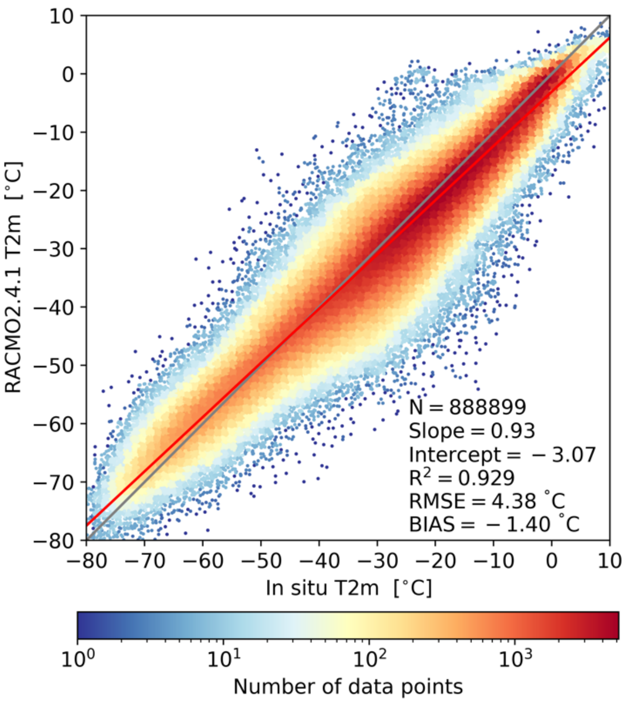

Figure 3: *RACMO2.4p1 2-m temperature (T2m) with respect to in-situ observations of the AntAWS data set that are scattered around the ice sheet. The total number of observations (N), determination coefficient (R^2), root-mean-square error (RMSE), bias and fit line are also shown. As version 2.4p1 was initially named version 2.4.1, the axis label differs in this figure.*

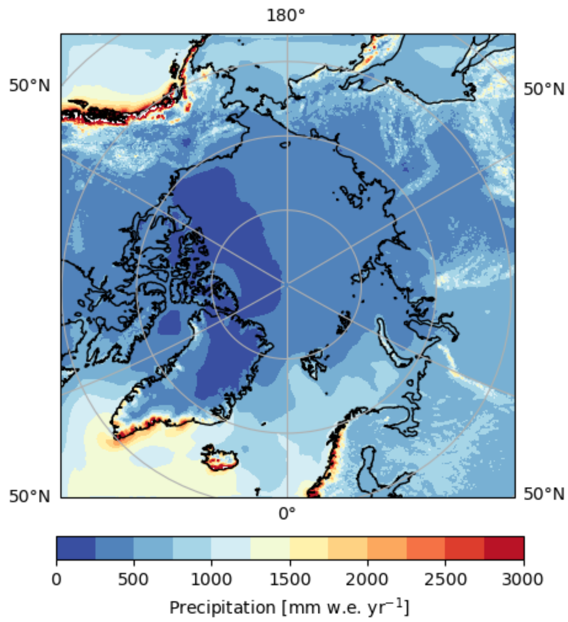

Figure 4: *Modelled annual precipitation for 1980-2022 by RACMO2.4p1, driven by ERA5.*

HCLIM (37 million SBU)

Setting up and testing HARMONIE-CLIMATE (HCLIM) in the Antarctic domain started in August 2022, and much of the work was done during 2023. After replacing the ice mask and topography for the new BedMachine Antarctica dataset, HCLIM was ready for running over small domains, using its non-hydrostatic HCLIM-AROME dynamics, and pan-Antarctic runs, using its hydrostatic HCLIM-ALADIN core. Several bugs were removed, but some issues persist, for example, using the Lambert conformal conic projection still leads to shifted (e.g. surface pressure) fields in the Southern Hemisphere. Therefore, a polar stereographic projection is used, even though this is not ideal. This technical work is done closely with DMI, KNMI, and MetNO.

The first scientific runs using HCLIM-AROME were started in 2023, over the Antarctic Peninsula, McMurdo Sound, and West Antarctica, all conducted under the PolarRES European project. HCLIM-AROME was run alongside other regional atmospheric (MAR, RACMO), oceanic (MetROMS-UHel) and coupled (MAR-NEMO) models to compare the representation of the basic sea ice characteristics: sea ice albedo, snow and ice thickness, and meteorological data during the melt periods of two Antarctic domains with very different sea ice conditions, using data of the ISPOL and Marsden field campaigns.

However, the first tests showed a surface temperature warm bias in HCLIM as large as 5 ℃ over sea ice compared to the ISPOL campaign measurements. The snow grain size used in the HCLIM snow albedo calculation is only a function of snow density and determines the reflectivity of snow to shortwave radiation, which affects surface meteorology, surface energy and mass balance. In the default HCLIM setting, it is an empirical relation from Anderson (1976) measured in a NOAA-ARS snow research station in Danville, Vermont, USA. The snow grain sizes in the Polar regions are known to be smaller. HCLIM snow grain size and density relation was updated using the output from the regional climate model RACMO version 2.3p3 (van Dalum et al., 2022), with its updated spectral snow albedo and radiative transfer scheme and the fresh snow grain sizes, which better correspond to Antarctic observations.
The left panel in Figure 5 shows the updated snow grain size to snow density relation together with the HCLIM default relation from Anderson (1976). The fresh snow albedo can reach a more realistic 0.85 with the improved grain sizes. The resulting differences in the total albedo fields are shown on the right panel in 5Z and are as large as 0.3.
This research is continued in 2024, leading to suggestions for an improved representation of sea ice albedo in HCLIM.

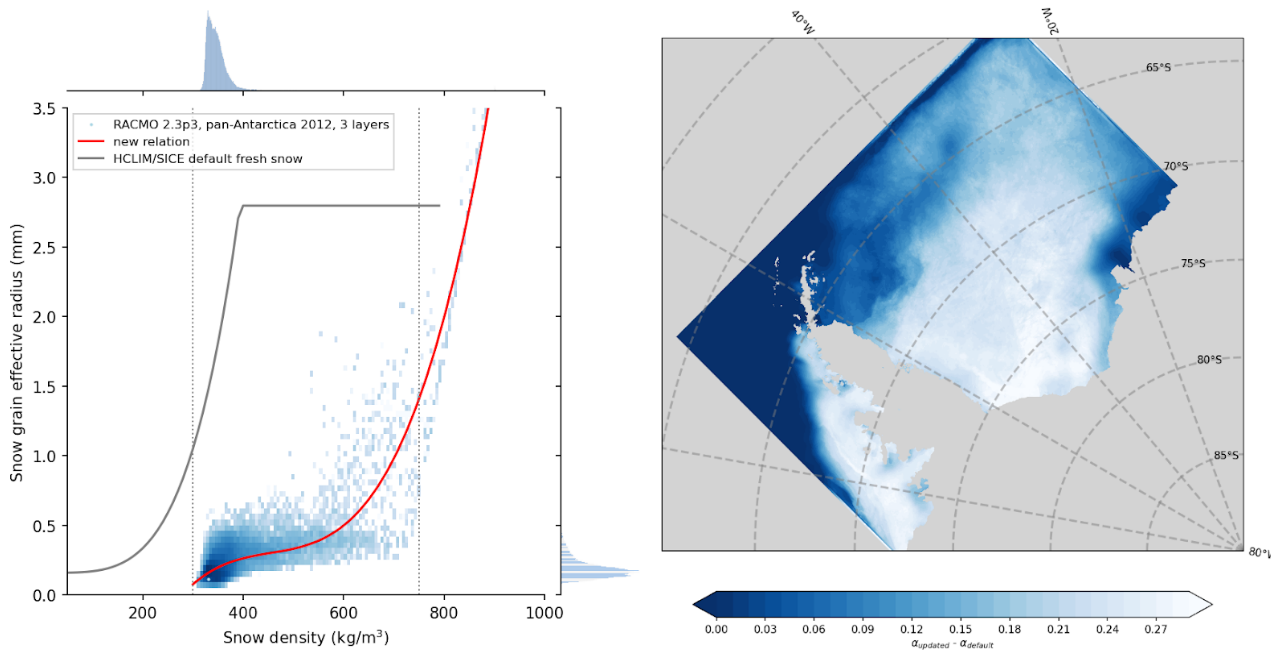

Figure 5: *RACMO2.3p3 2012 yearly snow density and snow grain sizes are shown as the density plot (blue shades), fitted third-order polynomial results in the updated HCLIM snow grain size to snow density relation (red solid line). HCLIM default relation is shown with a grey solid line. The dotted lines represent the snow density limits for sea ice in*

SICE and on land. Right: differences between HCLIM updated and the default setting mean albedo fields for December 2004.

Firn modelling using IMAU-FDM

The firn (multi-year snow) layer of ice sheets and glaciers is the top 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 Greenland Ice Sheet. The firn layer is porous, and as a result, it contains a significant amount of air. The firn air content (FAC), in the pore space of the firn, can be up to 30 m^3 per m. This allows meltwater to refreeze inside of it. Detailed information of the firn layer is needed to estimate, firstly, the evolution of the FAC, which is needed to compute the ice sheet's mass loss from satellite radar altimetry data. Secondly, to assess the future refreezing capacity of firn, and the associated future stability of ice shelves in Antarctica. For this aim, we model the evolution of the firn layers of the Antarctic and Greenland Ice Sheets 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 tasks, namely running many single core jobs, scripts have been developed to run IMAU-FDM efficiently in parallel, using 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.

Simulations for Antarctica: about 11 million SBU

Simulations over Antarctica for the contemporary climate (1979-2021) using the firn model FDM v1.2A have been performed in 2022 (Veldhuijsen et al., 2023). The simulations are forced by output of RACMO2.3p2 at a 27 km resolution. In 2023, these simulations were kept up to date by extending the simulations until December 2022, predominantly to meet the demand of the altimetry community (e.g., Davison et al., 2023). IMAU-FDM has also been used to perform projections of the evolution of firn layers till 2100 for various emission scenarios, as discussed below.

To perform future simulations, IMAU-FDM has been updated to version 1.2AD by implementing a complete transient dynamical firn densification expression (Veldhuijsen et al., 2024). This is needed to capture firn densification accurately in a transient climate. In the updated densification expression, overburden pressure and grain size are taken as state variables, instead of using simplifying assumptions of steady state accumulation and steady grain growth rate. We evaluated and compared this updated model version 1.2AD against in-situ firn core density measurements and previous model versions using a simulation forced by RACMO2.3p2, in turn driven by ERA5 boundaries. Next, Antarctic wide simulations of the firn evolution till 2100 under various emission scenarios using IMAU-FDM v1.2AD have been carried out. These simulations are forced by RACMO2.3p2, driven by CESM2 boundaries, for the scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5. These IMAU-FDM runs are used to project future FAC, 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 shelf disintegration.

Figure 6 shows results from these IMAU-FDM projections. Subfigures 6 a,b and c shows the relative total FAC change by 2090-2100 compared to 2005-2014. Over the grounded ice we find regions with increasing or decreasing FAC. On average, FAC for the grounded ice shelves decreases with 0.7%, 1.2% and 2.4% for scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5, respectively. We find decreasing FAC for most ice shelves under all scenarios. Increasing melt rates cause the formation of thick (>3 m) near-surface ice layers, which can impede vertical meltwater percolation to deeper firn, which limits the ability of the firn to refreeze meltwater. Therefore, we calculate the accessible FAC, i.e., the FAC that is accessible for meltwater. For this, we use ice layer thickness to estimate the permeability of ice slabs. Subfigures 6 d, e and f show the relative change in accessible FAC by 2090-2100 compared to 2005-2014. The accessible FAC is derived by estimating the impermeability of ice layers. Especially for SSP5-8.5 the depletion of the accessible FAC is accelerated compared to the total FAC, e.g., on relatively dry and cool ice shelves, such as Amery, Shackleton, Ronne-Filchner and Riiser-Larsen.

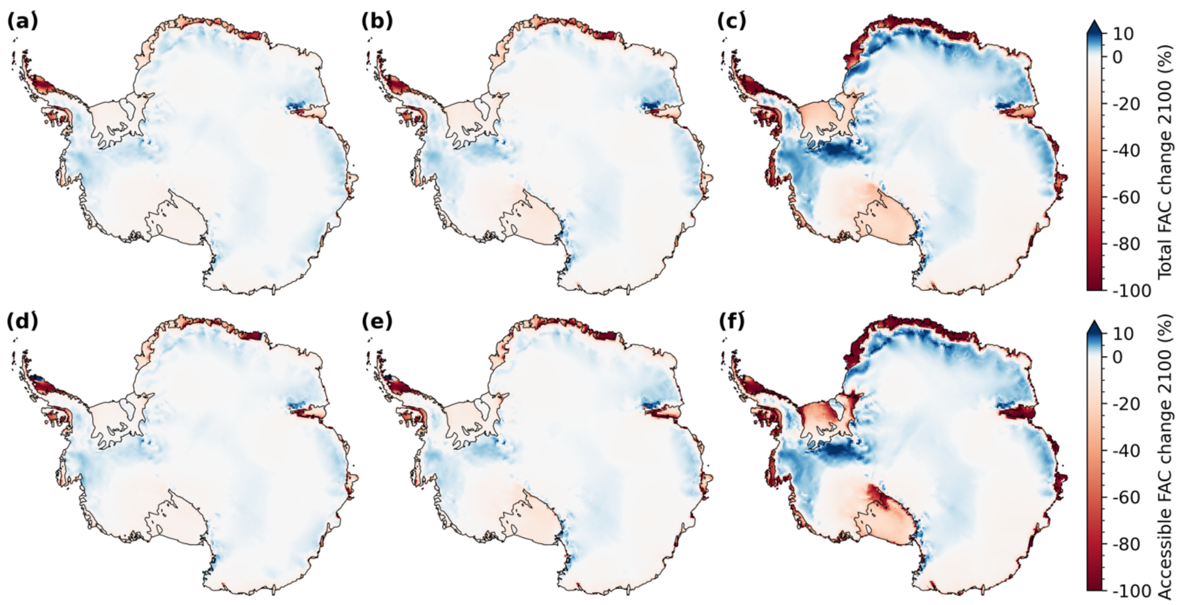

Figure 6: *Relative change in total firn air content (FAC) (top row) and relative change in accessible FAC (bottom row) by 2090-2100 compared to 2005-2014 for (a,d) SSP1-2.6, (b,e) SSP2-4.5 and (c,f) SSP5-8.5 compared to 2005-2014.*

Simulations for Greenland: about 2 million SBU

For the Greenland Ice Sheet, the output from the contemporary-climate run performed in 2022 was analyzed and interpreted, and it was found that thick ice slabs and water storage in aquifers around the Greenland perimeter is more widespread than what sparse observations suggest (Brils et al., 2024). It offers a more complete understanding of hydrological features in the Greenland firn. We constructed a phase diagram of firn features in a two-dimensional accumulation-melt space (Fig. 7), to show that the occurrence of such features is strongly driven by the surface climate, and that changes in the surface climate have a very direct control over the transition from one firn facies type to another. This is a powerful tool to predict future behaviour of the firn layer.

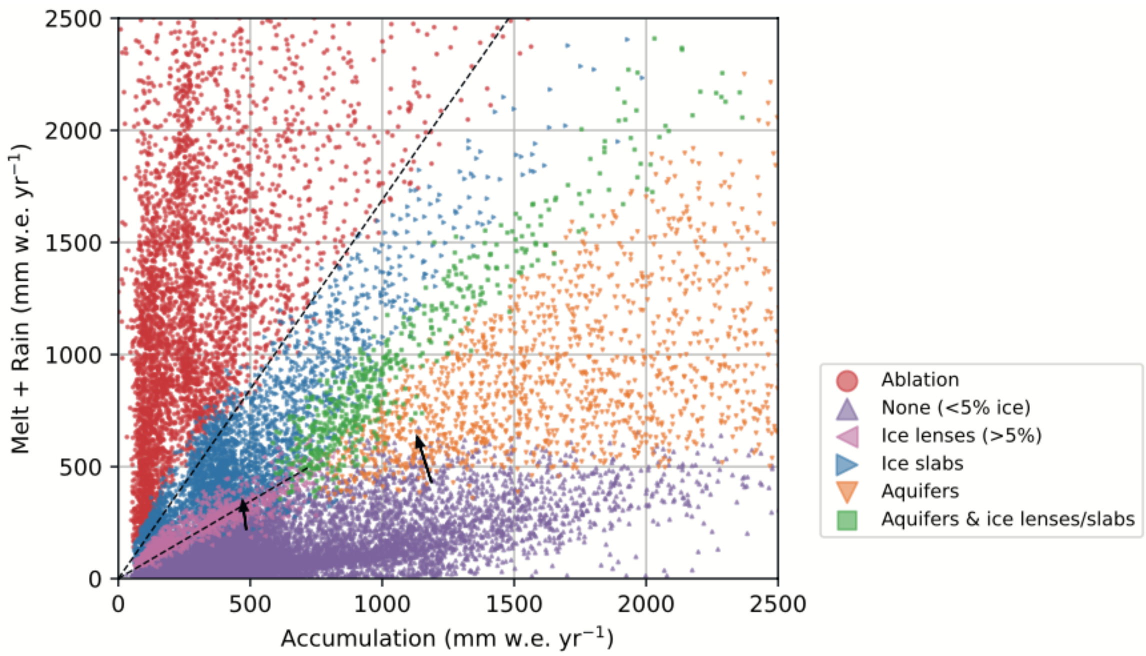

Figure 7: *The occurrence of thin ice lenses, thick ice slabs, and aquifers on the Greenland Ice Sheet, as a function of surface climate, represented by mean annual accumulation on the horizontal axis, and liquid water input on the vertical axis (in mm w.e. per year). The arrows show the climatic change from (1960-1980, arrow base) to (2000-2020, head) of two locations in the ablation zone.*

Further, in 2023 it was realized that runs of future Greenland firn evolution suffer from model deficiencies, specific to the Greenland Ice Sheet. It was decided to focus on a model reformulation, based on prognostic snow grain size, which resolves most of such issues. Some time and a limited amount of SBUs were spent on model development and testing. As shown in Figure 8, the new model formulation provides comparable performance to the old model with almost no loss of accuracy or increased bias (Brils, 2024), thus paving the way for future simulations planned for 2025.

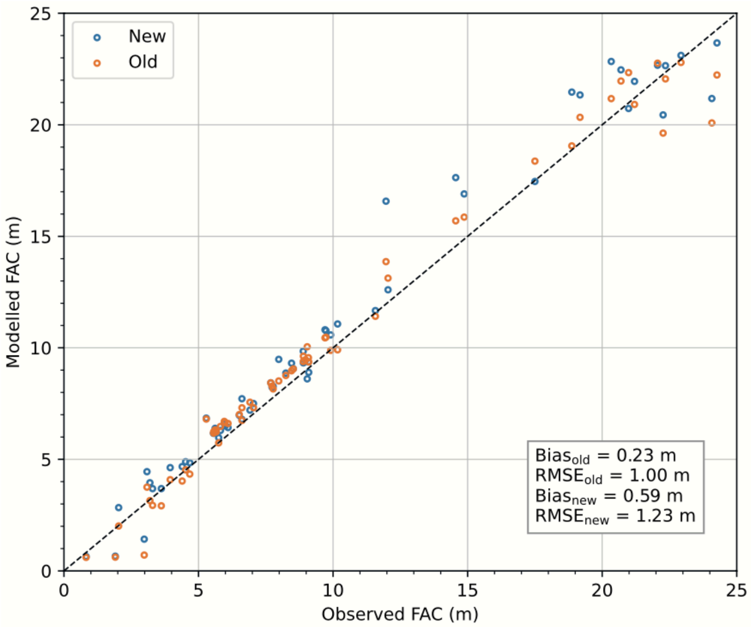

Figure 8: *Model performance of the old model formulation (orange) versus the model reformulation based on snow grain size, proposed by Brils (2024) (purple). Observed firn air content (FAC) in metres versus modelled FAC on the vertical axis.*

Deviations from the proposed plan for 2023

In the proposed plan for 2023, the following experiments were listed:

1. A CMIP6 model driven RACMO simulation (1980-2100) for both the Arctic and Antarctic. *This simulation has been postponed to 2024.*
2. Two pairs of 30-year time slice simulations (1980-2010 and 2070-2100) with RACMO for both the Arctic and Antarctica. *These simulations have been cancelled due to a different approach within the PolarRES project. Instead, we will run an additional pair of projections in 2024.*
3. The first of three long (1950-2300) simulations for Antarctica. *All three simulations are postponed to 2025.*
4. Run IMAU-FDM using the output of simulations 1 and 3. *Running IMAU-FDM using the projections till 2100 (experiment 1) is now proposed for 2025. IMAU-FDM simulations using output of experiment 3 is still planned after the completion of these simulations. No budget in 2025 has been requested for it, as it could well be that we will not be able to start these simulations in 2025.*
5. HCLIM simulations at 2 km resolution of the Antarctic Peninsula. *These simulations, albeit on 3 km, have been carried out, as described above.*
6. Extending our operational estimates of the climate of Greenland and Antarctica using RACMO2.4p1. *It was expected when the proposal was written that these operational simulations were run in 2022. So, instead of extending these simulations, we created those including the year 2023.*

List of publications/reports from the project with complete references

RACMO experiments:	
Greenland with 2.3p2:	Publication is in draft
Patagonia with 2.3p2:	Publication in in draft
Model development to version 2.4p1:	Van Dalum et al, 2024, in review
Snowdrift:	Gadde & Van de Berg, 2024, in review
Antarctica with 2.4p1:	Publication is in draft
Greenland and Arctic with 2.4p1:	Publication on both simulations is scheduled
HCLIM experiments:	Publication is in draft
Firn modelling:	
Antarctica:	Veldhuijsen et al., 2024, published
	A follow-up paper is in draft
Greenland:	Brils et al, 2024, published

Full references are given below

All data of these simulations will be shared on request. Key data (e.g. monthly means) will be published on Zenodo, however, this upload is not yet completed.

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 remained of 2024 are listed in the progress report of 2024. Our plans for 2025 are described and motivated in the special project proposal for 2025.

References

Amory, C. (2020). Drifting-snow statistics from multiple-year autonomous measurements in Adélie Land, East Antarctica. *The Cryosphere*, *14*(5), 1713-1725. https://doi.org/10.5194/tc-14-1713-2020

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Brils, M., Kuipers Munneke, P., van de Berg, W. J., & van den Broeke, M. (2022). Improved representation of the contemporary Greenland ice sheet firn layer by IMAU-FDM v1.2G. *Geosci. Model Dev.*, *15*(18), 7121-7138. https://doi.org/10.5194/gmd-15-7121-2022

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