EMI R&D 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	2026
Project Title:	**Modelling the climate and firn state in Antarctica and Greenland**
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)	N/A
Start date of the project:	2026
Expected end date:	2026

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)	130.000.000	42.836.399	105.000.000	30.405.325[1]
Data storage capacity	(Gbytes)	400.000	2.283.163	400.000	2.688.223[2]

[1] Data as of 28 June 2026.

[2] Data as of 10 June 2026.

Summary of project objectives

The SPNLBERG special project supports the RACMO and IMAU-FDM research groups at Utrecht University in their research of the climate of polar regions using the regional climate model RACMO and firn (multiyear snow) densification model IMAU-FDM. Our research philosophy is that through detailed model development and evaluations, process understanding is gained, leading to better parameterizations of key processes, materializing in improved reconstructions of the recent past climate and surface mass balance of the Antarctic and Greenland ice sheets as well as reliable projections for these ice sheets. The provided HPCF resources allow us to keep our estimates of the climate and firn state of the Greenland and Antarctic ice sheets up to date and to carry out model development. All model data will be shared after publication without restrictions, and since RACMO is one of the leading polar climate models, our data is yearly used in numerous (>45) scientific publications.

Summary of problems encountered

No HPCF or ECFS related problems were encountered.

However, both the development of RACMO version 2.4p2 as IMAU-FDM v1.3 took more time than anticipated in 2025, pushing planned simulations to the second half of 2026 or even 2027. As a result, less than half of the provided budget has been used and the granted budget, which was less than the requested budget, will likely be sufficient for the remainder of 2026.

Summary of plans for the continuation of the project

We continue the development of RACMO version 2.4p2, focussing on an improved representation of clouds and the snowmelt-albedo feedback. It is planned that for this development several shorter and longer RACMO simulations will be carried out. Furthermore, we start building a database of precipitation fields for various topographies of the Greenland Ice Sheet, which serve to train a versatile precipitation emulator. As part of a new PhD project, a long term (1950-2300) simulation of the Antarctic climate will be run, driven by ISPL data of scenario SSP5-8.5.

Also, the development of IMAU-FDM towards version 1.3 will be continued, focussing on the implementation of a novel water percolation scheme and on the representation of radiation penetration.

List of publications/reports from the project with complete references

As this project started January 2026, manuscripts have not yet been submitted.

Summary of results

For 2026, we requested budget for the following 5 projects:

1. Development of RACMO version 2.4p2.
2. Renew our operational estimates with RACMO for Antarctica and Greenland.
3. Generate a database of precipitation fields over the Greenland with different geometries.
4. High-resolution RACMO simulations for the Antarctic Peninsula.
5. Development of the firn densification model and operational firn modelling work

We discuss the work carried out for these projects below one-by-one.

1: Development of RACMO version 2.4p2

Four parallel research projects are running to support the development of RACMO version 2.4p2.

Cloud evaluation and cloud tuning using EarthCARE observations

Since the launch of EarthCARE in 2024, a satellite providing unprecedented remote sensing observations of clouds and their radiative impact, we use the EarthCARE data to evaluate and improve RACMO. In December 2025, all EarthCARE synergy products, which use multiple EarthCARE instruments, became publicly available. Of these products, we have mainly used the synergetic ACM-CAP product, which combines observations from the lidar, radar, and multispectral imager.

Both the Antarctic and Greenland runs have been extended to the end of April 2026 giving us 20 months to compare EarthCARE observations with RACMO simulations. We used the method developed in the previous year (Feenstra et al., 2026) to aggregate all EarthCARE overpasses onto the RACMO grid to be able to compare the model and observations.

These comparisons have proven extremely useful for model development purposes: they show that RACMO underestimates cloud occurrence in both cloud phases over ice- and snow-covered regions (ice sheets, snow-covered land, and sea ice), but overestimates cloud occurrence over open ocean (Fig. 1). However, for all regions the ice water path is underestimated. Additionally, RACMO misses high-altitude thin ice clouds frequently and underestimates the heights of supercooled liquid layers. Regarding snowfall, we see that this occurs too frequently over the open ocean and at the ice sheet margins, while it is not modeled frequently enough over the ice sheet interior and sea ice. On the other hand, the snowfall intensity is underestimated over the entire domain.

After identifying biases in RACMO’s cloud representation, we performed several tests regarding parameterizations in the cloud microphysical and the radiation scheme. Here, we found that the modeled clouds are relatively sensitive to the parameterization for ice crystal number concentration, cloud droplet number concentration, critical threshold for autoconversion to snow, and the ice and snow fall speeds. Additionally, we found sensitivity towards the representation of the ice and liquid cloud content in the radiation scheme.

Finding the optimal configuration of model parameterizations and constants for these processes is part of our planned work for the second half of 2026. Furthermore, we plan to make updates to the handling of the convective precipitation, investigate the parameterization of homogeneous nucleation, and do sensitivity tests with the radiation scheme during clear-sky conditions. Parallel to these sensitivity tests, we already developed and tested a new parameterization for the fall speed of precipitating snow. EarthCARE, carrying the first Doppler radar in space, can provide us with estimates of the fall velocity of precipitation. These observations were used to develop a parameterization that relates the fall speed of snow to temperature and ice water content, replacing the constant fall speed of 1 m/s that is currently in place. Implementation of this new parameterization for a winter and a summer month for the Antarctic domain showed that the representation of high-altitude clouds could be slightly improved and that clouds with high ice water content are better represented.

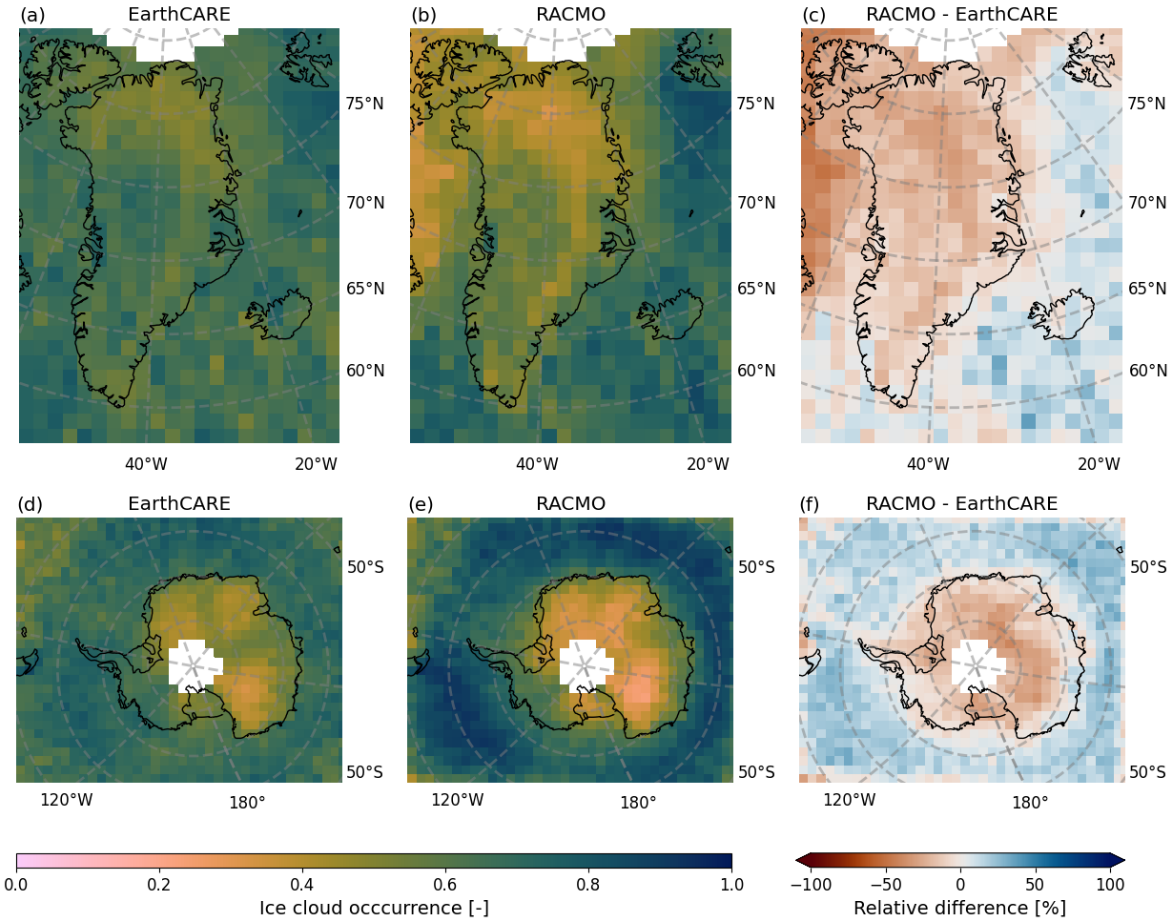

Figure 1: *Ice cloud occurrence over **(a-c)** the Greenland domain and **(d-f)** the Antarctic domain during EarthCARE overpasses (Augustus 2024 to April 2026) for **(a,d)** EarthCARE observations, **(b,e)** RACMO model output, and **(c,f)** the relative difference between RACMO and EarthCARE.*

Surface roughness sensitivity tests

The latest RACMO2.4p1 version was run for the Greenland 5.5km domain for the period 2020-2021, a period with available eddy covariance observations from the surface of the Greenland Ice Sheet. Four different simulations were performed using various surface roughness parameterisations: with-and-without an updated aerodynamic roughness formulation for snow and ice based on van Tiggelen et al. (2021), and with-and-without a formulated scalar roughness length updated to the model from Yang et al. (2008). These simulations led to some bug fixing and to the release of version '6' of 2.4p1.

The 4 simulations with bugfixes were performed once again for the longer period 2020-2022. An additional simulation was done with 65 vertical layers, instead of the 40 that are used by default, to quantify the effect of vertical resolution on turbulent exchange processes near the surface. The vertical profiles simulated by RAMCO2.4p1 were evaluated using tethered balloon observations acquired in 1991, and against the latest CARRA2 reanalysis product. Figure 2 demonstrates the effect of adapted surface roughness parameters on the near-surface temperature and wind gradients, sensible heat flux and surface runoff over the Greenland Ice Sheet. The main finding is that including a more realistic aerodynamic roughness formulation for ice, based on satellite altimeter observations, in combination with a different formulation for scalar roughness lengths, leads to 9% more yearly total runoff from the ice sheet. These results have been written in the form of a scientific article and has been submitted at the start of July 2026.

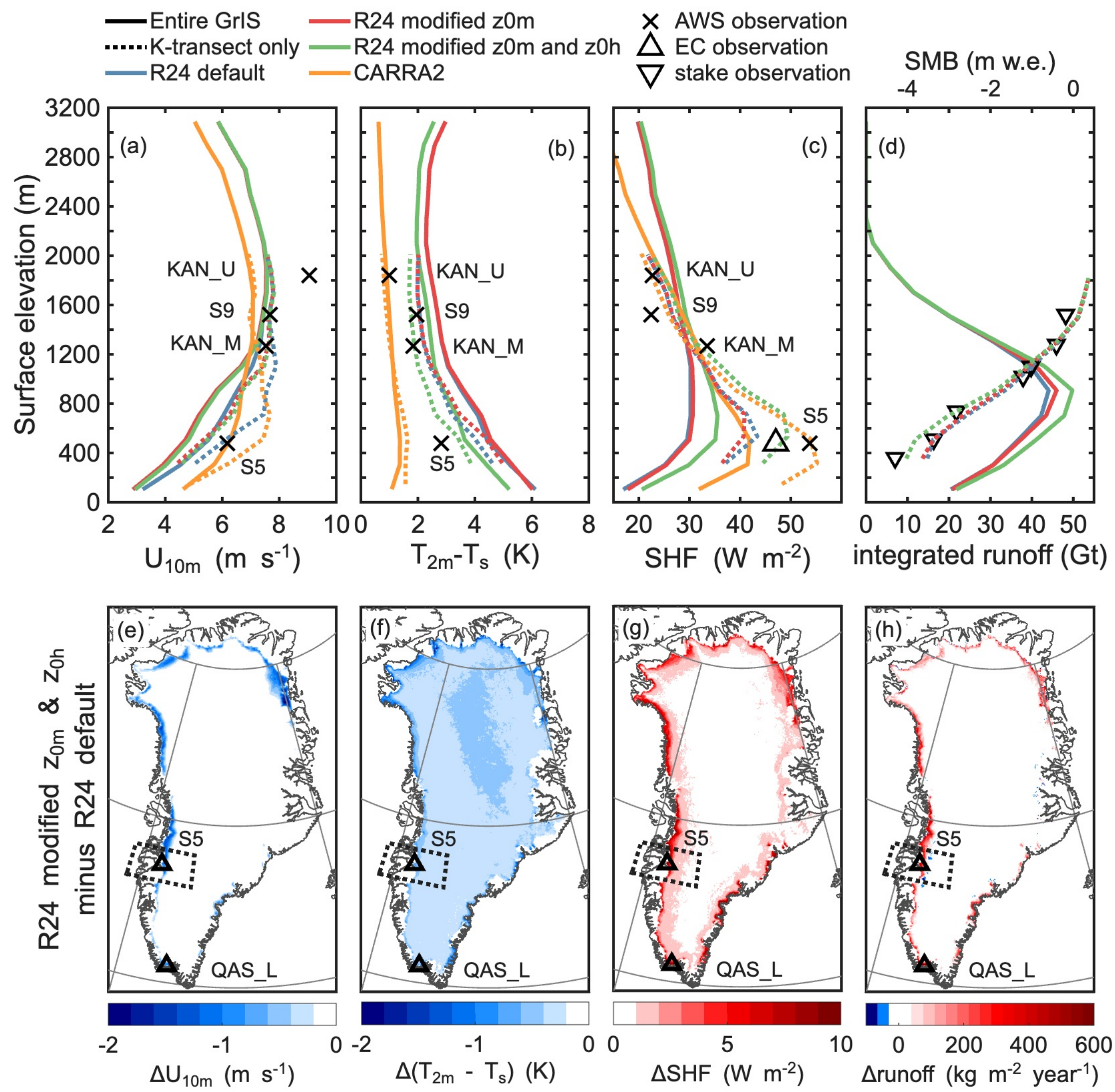

Figure 2: *Yearly averaged* ***(a)*** *10-metre wind speed,* ***(b)*** *near-surface temperature gradient,* ***(c)*** *sensible heat flux (SHF), all averaged with per elevation bin.* ***(d)*** *Yearly integrated runoff per 100 m elevation bin.* ***(e-f)*** *change in yearly averaged change in 10-metre wind speed, near surface temperature gradient, and SHF respectively.* ***(h)*** *change in yearly runoff. All data is for 2021. The lower row displays the difference between the default RACMO2.4p1 simulation and the updated version with modified z_{0m} and z_{0h}. The location of the sites used for the evaluation are also shown, with KAN_M, KAN_U and S9 being all close to station S5. Figure from Van Tiggelen et al (submitted).*

Bare ice retention tests

We performed some sensitivity tests to investigate the importance of meltwater refreezing in bare ice, a unique feature in RACMO2.4p1. Several simulations were performed for the period June-July-August 2016, a period with subsurface ice density measurements on the Greenland Ice Sheet. We found that depending on model parameters such as ice effective porosity, bare ice refreezing can potentially reduce the total runoff form the ice sheet by up to 10% (Fig. 3). Based on these results we have decided to plan a new observation campaign on the ice sheet in summer 2026. The first part of this campaign has been successfully executed. A visiting master student from Toulouse will analyse the observed and modelled bare ice retention in the summer of 2026.

Snow albedo tests

Besides these activites, a few short (2-month) simulations have been done to do first tests to improve representation of snow albedo in Greenland for the upcoming RACMO2.4p2 version. This effort will be continued in the remainer of 2026.

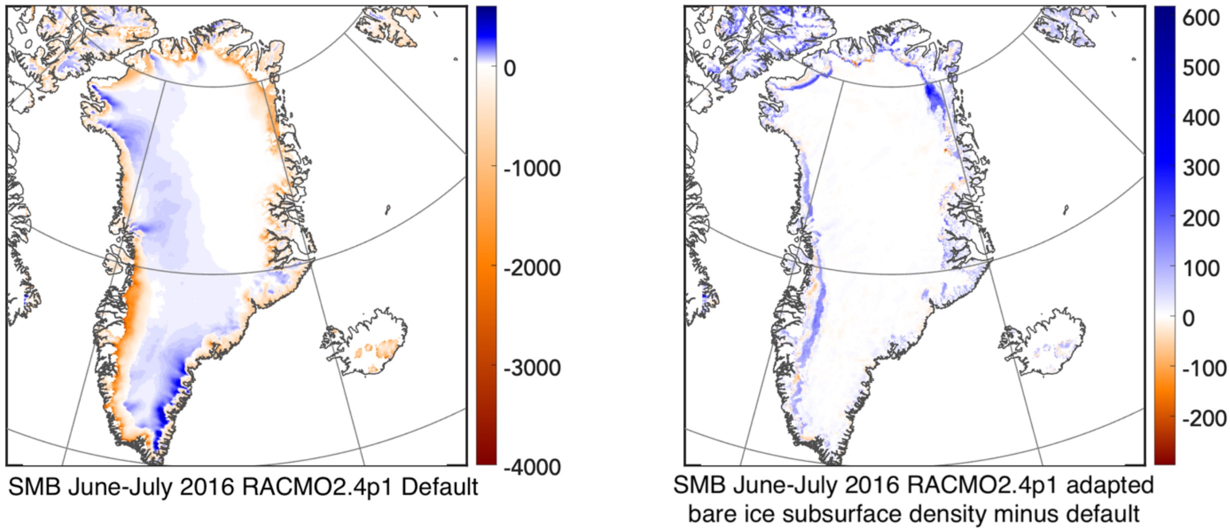

Figure 3: *Effect of including bare ice refreezing in RACO2,4p1 in the period June-July 2016.* ***(left)*** *The simulated cumulative surface mass balance by the default model version (in mm w.e).* ***(right)*** *The difference of the updated model version minus the default version (in mm w.e).*

2: Renew our operational estimates with RACMO for Antarctica and Greenland

The planned renewal of RACMO operational runs for Antarctica and Greenland using RACMO2.4p2 were not done yet as we are still working towards the new RACMO2.4p2 version. Nevertheless, the existing operational simulations were extended in the first half of 2026. The Antarctic simulation was extended from February 2025 until February 2026 using RACMO2.4p1 and the operational simulation of RACMO (using version 2.3p2 in anticipation of the model update) for Greenland was extended until February 2026. In addition to the operational simulations, the 11 km Arctic RACMO simulation forced by ERA5 was extended through the end of 2025. Lastly, to support the continuation of existing IMAU-FDM simulations for Antarctica, the 27 km Antarctic RACMO2.3p2 simulation was also extended through the end of 2025.

3. Generate a database of precipitation fields with different geometries.

We have started work on this objective by running a first reference simulation for a new 16.5 km Greenland domain. This domain is computationally more efficient and will allow us to perform a wide range of simulations to generate precipitation data for training the rapid Greenland Ice Sheet precipitation emulator, for use in e.g., ice sheet model simulations extending over millennia. The reference simulation is a historical run forced by CESM2, covering the period 1950–2014. Currently, an emulator version has already been developed that successfully can reproduce the simulated precipitation fields over the contemporary geometry.

In addition, initial tests (simulations extending over several months) have been carried out using a modified Greenland Ice Sheet geometry. These tests show that RACMO can successfully be used to simulate the impact of changes in ice sheet geometry on precipitation fields, which will be performed in the second half of 2026. Figure 4 shows the accumulated precipitation over a three-month period for the present-day Greenland Ice Sheet geometry compared with a modified geometry representative of the year 3000, assuming greenhouse gas concentrations increase until 2100 under a very high-emissions scenario and then remain constant until 2300. The initial test shows a very non-linear response of precipitation to ice sheet geometry change. The inland shifted southwestern ice sheet margin becomes wetter, related to the increased ice sheet surface slope, while the tundra and surrounding seas become dryer.

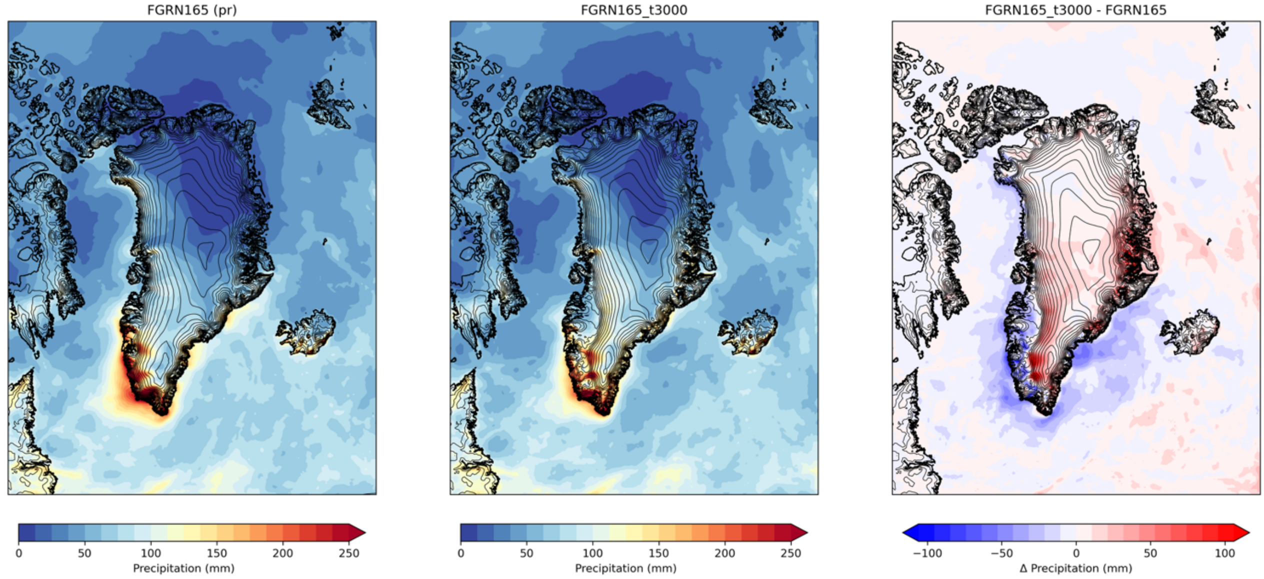

Figure 4: (left) *Modelled precipitation for the current Greenland Ice Sheet geometry.* ***(middle)*** *Modelled precipitation for an estimated ice sheet geometry for the year 3000, using the exact same Earth System Model weather fields at the lateral boundaries.* ***(right)*** *Difference in modelled precipitation.*

4. High-resolution RACMO simulations for the Antarctic Peninsula

As described in the SPNLBERG 2025 final report, an ERA5-driven RACMO 2.4p1 simulation for the Antarctic Peninsula has been carried out in the second half of 2025. This simulation, which is the first of several simulations planned for 2026, is currently being analysed. The analysis shows that for optimal projections of the firn evolution over the Larsen C Ice Shelf of the Antarctic Peninsula the spatial patterns of snow melt should be improved. Further simulations for the Antarctic Peninsula are, therefore, postponed until RACMO version 2.4p2 is released, which, hopefully, provides an improved spatial representation of snow melt over the Larsen C Ice Shelf.

5. Development of the firn densification model and operational firn modelling work

The existing simulation of IMAU-FDM for the firn layer over the Antarctic Ice Sheet was updated to 31 December 2025. For Antarctica, there is now a consistent data set of firn changes available from 1979 through 2025 to be used for mass balance studies and interpretation of satellite altimetry and stereoscopy.

A recent paper by Bernat et al. (2026) (including co-authors from our IMAU-FDM team) gives unprecedented detail of mass loss in the Antarctic Peninsula (Fig. 5). This is a geographically challenging area, for which a revised mass balance estimate at high resolution - and using a firn correction term from IMAU-FDM - shows that the mass loss over the last two decades has been a factor 4 to 5 larger than reported previously. This result continues to draw attention to this fragile and fast-changing part of the cryosphere.

Next to this extension of our operational Antarctic firn simulation, we continued developing IMAU-FDM version 1.3. Besides updated firn densification and surface snow density parameterizations, as listed in the 2026 project proposal, we also plan to update the description of water percolation in IMAU-FDM. However, before updating the water percolation scheme, we first need an evaluated description of the effective grain size, which is required to compute the permeability of firn. Therefore, we are currently testing different grain size parameterizations in the model at several example locations.

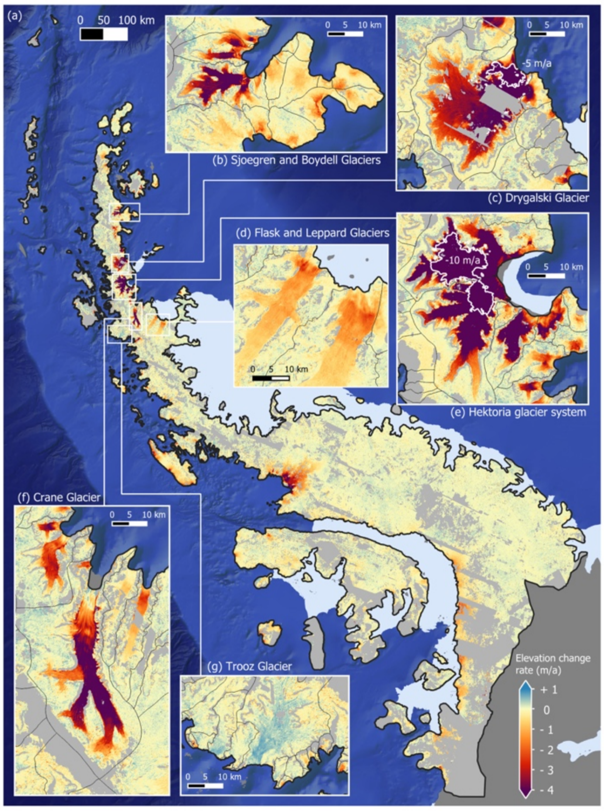

Figure 5: *Elevation change rates over the Antarctic Peninsula between 2007 and 2021. Five catchments are highlighted in the insets* ***(b)*** *to* ***(f)****, with Silva et al. (2020) catchment outlines plotted in thin black lines. On* ***(c)*** *and* ***(e)****, the white line indicates the −5 and −10 m a*$^{-1}$ *delimitation. The background oceanic hillshade and the ice shelves outlines come from BedMap3. Figure from Bernat et al. (2026).*

References:

Bernat, M., Berthier, E., Dehecq, A., Hugonnet, R., Belart, J. M. C., Ochwat, N., Kuipers Munneke, P., Case, E., Scambos, T., Gauer, L. M., & Youssefi, D. (2026). Mass changes of the Antarctic Peninsula ice sheet and peripheral glaciers, 2007–2021. *The Cryosphere*, *20*(5), 3025-3049. https://doi.org/10.5194/tc-20-3025-2026

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