REQUEST FOR A SPECIAL PROJECT 2021–2023

MEMBER STATE: Netherlands

Principal Investigator[1]: Dr. Willem Jan van de Berg

Affiliation: Utrecht University
Institute for Marine and Atmospheric Research Utrecht (IMAU)

Address: Princetonplein 5
3584 CC, Utrecht
The Netherlands
+31 30 253 3273

Other researchers: Dr. Brice Noël, Dr. Melchior van Wessem, Dr. Carleen Reijmer, Dr. Peter Kuipers Munneke, Max Brils and Maurice van Tiggelen (UU/IMAU)
Dr. Erik van Meijgaard (KNMI)

Project Title:

The contemporary and projected climate of Greenland and Antarctica

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** NLBERG	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2021	
Would you accept support for 1 year only, if necessary?	YES	NO

Computer resources required for 2021-2023: (To make changes to an existing project please submit an amended version of the original form.)		**2021**	**2022**	**2023**
High Performance Computing Facility	(SBU)	30.000.000		
Accumulated data storage (total archive volume)[2]	(GB)	200.000		

Continue overleaf

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

Principal Investigator: Dr. Willem Jan van de Berg

Project Title: The contemporary and projected climate of Greenland and Antarctica

Extended abstract

The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF as well as the Scientific Advisory Committee. The evaluation of the requests is based on the following criteria: Relevance to ECMWF's objectives, scientific and technical quality, disciplinary relevance, and justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests asking for 1,000,000 SBUs or more should be more detailed (3-5 pages). Large requests asking for 10,000,000 SBUs or more might receive a detailed review by members of the Scientific Advisory Committee.

Summary

In the last decades, the Antarctic Ice Sheet (AIS) and Greenland Ice Sheet (GrIS) are increasingly contributing to global mean sea level rise (The IMBIE Team, 2018; 2020) in response to regional atmospheric and oceanic warming. For the GrIS, atmospheric warming leads directly to enhanced mass loss through ablation. For the AIS, atmospheric warming indirectly increase mass loss as enhanced snow melting can destabilize buttressing ice shelves in Antarctica, enhancing ice discharge into the ocean. Accurate estimates of contemporary and projected ablation and snow melt require dedicated high-resolution atmospheric models as several feedback processes enhance melt during the summer season (e.g. Jakobs et al, 2019; Van Dalum et al, 2020). To provide these accurate estimates, we propose as our main research tool the polar adapted version of the regional atmospheric model RACMO2.

For the continuation of research projects within the framework of international cooperation, we request HPCF and ECFS resources for:

1. Updating our operational estimates with RACMO2 of the climate and surface mass balance of the Antarctic and Greenland ice sheets and their peripheral glaciers. These estimates are widely used by scientist all over the world.
2. Performing projections with RACMO2 of the future climate and surface mass balance for both ice sheets under both a high-mitigation and low-mitigation scenario. These projections will be used in an international effort to narrow down uncertainties in the projected contribution of both ice sheets to global sea level rise.
3. Assessing contemporary and future changes in the multiyear snow column covering the AIS and GrIS and the subsequent impacts on mass loss and ice shelf stability.
4. Test and evaluation simulations with RACMO2.4p1, in which the whole package of parameterizations of physical processes is updated.

Motivation

A major potential threat of future climate change is sea level rise. While the local sea level rise may differ from the global mean sea level rise (GMSLR), the local change and its uncertainty is dictated by the GMSLR. For different reasons, the Antarctic and the Greenland Ice Sheets and their peripheral glaciers will significantly contribute to it (e.g. Church et al, 2013), but their contributions have, even for a given projection, considerable uncertainty.

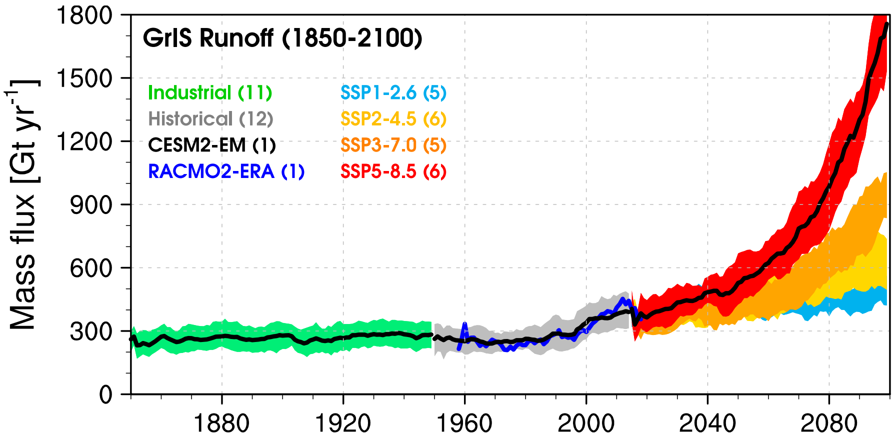

Figure 1: *Time series of Greenland Ice Sheet (GrIS) integrated runoff from various CESM2 simulations statistically downscaled to 1 km resolution for the period 1850-2100. In green the industrial period (1850-1949; 11 members), in grey the historical period (1950-2014; 12 members), in cyan, yellow, orange and red are scenarios SSP1-2.6 (2015-2100; 5 members), SSP2-4.5 (6), SSP3-7.0 (5) and SSP5-8.5 (6) respectively. The black line shows the CESM2 ensemble mean under a SSP5-8.5 scenario. The blue line shows the reanalysis-forced RACMO2.3p2 simulation for the period 1958-2018 (Noël et al., 2019).*

The Greenland Ice Sheet (GrIS), and peripheral glaciers and ice caps (GICs) are firstly losing mass due to atmospheric warming, leading to more ablation and subsequently a reduced or negative surface mass balance (SMB) (e.g. Noël et al, 2019). Secondly, ice discharge from marine terminating glaciers is enhanced due to atmospheric and oceanic warming (Mankoff et al, 2019). For the GrIS, enhanced ablation and ice discharge are each responsible for about half of the mass loss, respectively; for GICs the mass loss is primarily due to enhanced ablation (Van den Broeke et al, 2016; The IMBIE Team, 2020). With the higher climate sensitivity of the new generation of ESMs participitating in CMIP6 (e.g. Zelinka et al, 2020), the mass loss from the GrIS may accelerate faster than previously thought. For example, meltwater runoff may quintuple before the end of the 21st century in case of unabated warming (Fig. 1). It is, therefore, essential to narrow down uncertainties on the projected mass loss for a given mitigation scenario and to improve our understanding of the ongoing increase of GrIS mass loss.

The Antarctic Ice Sheet (AIS) is losing mass due to the dynamic interaction between ice flow and ocean-driven melt below the floating ice shelves that fringe the Antarctic coast (The IMBIE team, 2018). Nonetheless, atmospheric processes play an important role as warmer conditions lead to an increase of melting over the ice shelves. Once that melt water can no longer refreeze, melt ponds may lead to fracturing and subsequent disintegration of the ice shelves, as has been observed for the Larsen A and B Ice shelves in the Antarctic Peninsula (e.g. Banwell et al, 2013). As ice shelves buttress the ice discharge from the AIS, disintegration of ice shelves will cause enhanced mass loss from the AIS and accelerated sea level rise (Fürst et al, 2016). Many studies (e.g. Cornford et al, 2015; DeConto and Pollard, 2016) indicate that future mass loss from the AIS may accelerate rapidly and irreversibly due to the Marine Ice Sheet Instability (see e.g. SROCC report (IPCC, 2019)). However, it is heavily debated if this threshold for irreversible multi-metre GMSLR mass loss will be crossed for unabated climate change only, or that it will be crossed soon or if the threshold has already been crossed, and at which pace the AIS would lose mass once irreversible mass loss has started. Even though the SMB and snow melt are not the key processes for the stability of the AIS, accurate projections are essential to improve our understanding of the fate of the AIS in the coming centuries.

Accurate estimates of the SMB, snow melt and ablation require a detailed and physically-based representation of precipitation generation and surface processes over glaciated regions. For example, even though snow and ice melt and subsequent ablation are clearly linked to temperature, the occurrence and magnitude of melt is largely determined by the albedo (shortwave reflectivity) and the efficiency of turbulent heat transfer in the typically stratified atmospheric boundary layer (Box et al, 2012). Furthermore, once melt occurs, the capacity of the firn (multiyear snow) layer to refreeze or retain this meltwater determines whether meltwater can runoff or not (e.g. Noël et al, 2017). As the albedo, turbulent heat transfer, and firn processes all include positive feedbacks, the SMB can vary from a local surface mass loss of 4 m per year to no mass loss over a vertical elevation difference of only 500 meters, due to temperature differences, or tens of kilometres horizontally, due to spatial variations in precipitation. For accurate estimates of melt and SMB, high resolution (atmospheric) models, with detailed physical representation of the various processes in the snow and ice column that determine the surface albedo and meltwater buffering, are thus required. Although Earth System Models and reanalyses steadily improve in their spatial resolution and physical representation of glaciated surfaces, most accurate estimates of the contemporary and future climate and SMB of the AIS, GrIS and GICs are still derived with dedicated (i.e. polar adapted) regional atmospheric climate models (RCMs) (e.g., Fettweis et al, 2020; Mottram et al, 2020). RCMs, like RACMO2 as described below, are atmosphere only models and hence lack dynamic feedbacks with the sea ice and the ocean. As our research aims to focus on the climate over land ice, two-way coupling of the atmosphere with the ocean is not essential; providing dynamic boundary conditions on the sea surface temperature and sea-ice coverage is sufficient.

In brief, it is essential to understand the current and to project the future melt and SMB of the AIS, GrIS and GICs are essential for accurate predictions of GMSLR. To address this, dedicated RCMs are the most suitable numerical tools.

Methods

We plan to use the Regional Atmospheric Climate Model RACMO2, statistical downscaling and the firn densification model FDM for the proposed research below.

RACMO2

RACMO2 is one of the leading RCMs in this research field and has been used for hundreds of studies of the SMB and climate of the AIS and GrIS and its peripheral glaciers, as well as other glaciated areas, e.g. the Canadian Arctic and Patagonia (e.g. Lenaerts et al, 2013; Van Wessem et al, 2018; Noël et al, 2019). RACMO2 is developed and maintained by the Royal Netherlands Meteorological Institute (KNMI) and the operational polar versions (RACMO2.3p2 and RACMO2.3p3) consist of the dynamics of HIRLAM, version 5.0.6, and ECMWF IFS physics version CY33R1. In the polar version, interactive multi-layer snow model which includes firn densification, drifting snow processes, meltwater percolation, retention and refreezing and an albedo parameterization based on snow grain size evolution are added in order to represent the surface processes of glaciated areas. In version RACMO2.3p3, the broadband snow albedo model is replaced by a narrowband albedo model, which much better handles the highly spectrally variable nature of both the snow albedo as the incoming short-wave radiation. Like HIRLAM, RACMO2 is a fully parallel model with separated I/O and along with RACMO2 model code comes a suite of batch pre- and postprocessing scripts. RACMO2 is typically run on 300 to 800 logical cores at the supercomputing facilities of ECMWF.

In 2021, we plan to update the IFS physics embedded in RACMO to IFS cycle CY41R2 or newer. The primary improvement will be the representation of clouds, cloud phase, cloud microphysics and precipitation formation and advection. These changes will likely improve the representation of polar clouds and their impact on the climate in RACMO2, as polar clouds tend to remain liquid despite the low temperatures due to absence of proper nuclei, and advection of falling snow becomes significant on the resolutions – 5.5 km to 27 km - at which RACMO2 is run. Furthermore, we plan to update the surface roughness parametrization in the new version. The main change will be to prescribe a map of surface roughness, based on new satellite altimeter observations. This will likely improve the heat and momentum exchange over a rough ice surface, and thus improve the modelled SMB.

Statistical downscaling

Even though RACMO2 is run typically at 5.5 km resolution, this resolution is not enough to resemble all spatial SMB patterns in the ablation zone. Therefore, for Arctic glaciers, ice caps and the GrIS the SMB is further statistically downscaled to a 1 km (Greenland) or 500 m (elsewhere) grid, which better resolves the smaller glaciers and ice caps in those regions. This downscaling procedure includes elevation and albedo corrections using as many as possible available SMB observations from the region of interest. As a result, the downscaled data provides superior estimates of the local and integrated SMB compared to the normal SMB estimates of RACMO2 (e.g. Noel et al, 2016). Statistical downscaling programs are run on single cores and require limited HPCF and ECFS resources.

Firn densification model FDM

As part of a series of adaptations to represent faithfully the atmosphere - ice-sheet interaction, RACMO2 has been equipped with a detailed physical firn model. Nevertheless, the vertical resolution for buried snow and ice layers is limited due to computational and memory limitations. Therefore, the vertical firn profiles are refined using the firn densification model FDM, which uses more vertical layers than the snow model in RACMO2 (Steger et al, 2017; Ligtenberg et al, 2018). Moreover, such a stand-alone firn model enables easier model development, better spin-up, and better constraint on model uncertainty. By using FDM, a more accurate estimate of melt water retention, refreezing and snow compaction-induced surface elevation changes is obtained.

Proposed experiments for 2021

1. In 2020, we have started to use ERA5 as forcing for our reanalysis driven operational estimates of the climate and SMB of the AIS, GrIS and peripheral glaciers on Greenland. For the AIS, RACMO2 is run with a resolution of 11 km, while the model domain covering Greenland has a resolution of 5.5 km. Subsequently, SMB estimates for the GrIS and its peripheral glaciers are statistically downscaled to 1 km resolution. As these products are in high demand in the scientific community, we keep these estimates up to date in 2021. In order to keep the time lag of our products down to one to three months, we will use ERA5T data and rerun segments if errors were observed in ERA5T later on.

   For this task we estimate the HPCF costs on 1 MSBU and the ECSF demand on 5 TB.

2. Within the framework of the H2020 project PROTECT, we will perform one historic realisation (1950-2014) and two scenario realizations (2015-2100) for both the AIS (27 km) and GrIS (11 km). The two scenarios to be investigated will be the SSP1-2.6 and SSP5-8.5 scenarios, covering the full width of possible mitigation efforts. The results for Greenland will be statistically downscaled to 1 km resolution. In the second half of 2020, we will decide, in coordination with PROTECT project partners, which CMIP6 model will be used for these simulations. These simulations will be complementary to the RACMO2 simulations forced by the CMIP6 model CESM2, which will be completed in 2020.

   For the Antarctic domain, HPCF and ECFS demands are 35 kSBU and 0.25 TB per year, respectively. For the domain covering Greenland, these demands are 60 kSBU and 0.45 TB per year. For 235 model years for both domains, these costs sum up to 22.3 MSBU of HPCF usage and 160 TB of ECFS capacity.

3. In order to refine our operational and projected estimations of changes in the firn column, we will use the firn densification model IMAU-FDM. In 2021, we focus our model development on representation of water processes in firn and the evolution of firn aquifers (perennial liquid water at typically 15 to 50 m below the surface) and percolation-blocking sub-surface ice lenses in a warming climate. In particular, pronounced inland extension of the regions with sub-surface ice lenses would imply that the melt water buffering capacity of the GrIS to increasing melt is less than previously thought.

   For this task, 3 MSBU HPCF resources and 10 TB of ECFS storage facilities are requested.

4. As discussed above, in 2021 we update the physics package in RACMO2. We request a modest number of resources for testing and initial evaluation simulations of the updated version, RACMO2.4p1, namely 1.0 MSBU of HPCF and 10 TB of ECFS resources.

Applications and rationale

The primary reason to grant this proposal is the significant scientific and societal impact that the results of RACMO2 and the refined products have. Our operational estimates of the climate and SMB of the AIS and GrIS are used by numerous scientists. Our operational data is freely available on request. For example, since January 2019, statistically downscaled data SMB data for Greenland, Canadian Arctic or Svalbard is shared 101 times; native RACMO2 data of the operational dataset for Greenland has been shared 37 times. Data of our operational Antarctic dataset is shared 22 times since January 2019. As result of our open data sharing policy and the renowned quality of our products leads to that RACMO data is used in over 500 scientific publications, reports and presentations on GrIS and AIS climate and mass balance (based on a search in

Google Scholar using "RACMO **and** Greenland **or** Antarctica”). Our model results have been used in past IPCC reports like the recent SROCC report, all major ice sheet mass balance review studies (e.g. The IMBIE Team, 2018; 2020), and will be used in the upcoming synthesis report.

Similarly, the proposed historic and projected climate realisations for the AIS and GrIS will help the scientific community to reduce or quantify the uncertainties of the expected global mean and local sea level rise. These simulations will be carried out within the EU funded H2020 project PROTECT. Within this project, all aspects of the mass balance of the two ice sheets are considered, thus ice dynamics, ice-ocean interactions, ice-bedrock interactions, atmosphere-ice shelf-ocean interactions and atmosphere-ice sheet surface interactions. Our projections will be used to drive ice sheet models, estimate future mass loss by enhanced ablation and to determine the future (in)stability of Antarctic ice shelves. Even though our projections are carried out within the framework of PROTECT, the data will be freely available after completion of the simulations.

We chose for an approach with a limited number of realisations on high resolution, as the chaotic dynamical spread on a limited area domain around the realisation of the ESM is relatively limited. In contrast, ESM realisations for equal boundary conditions do show a significant dynamical spread. For our purposes, the loss of spatial detail, a consequence of targeting multiple realisations, thus does not outweighs the gain in knowledge of non-linear effects that might amplify differences between scenario realisation members. However, as realisations of a different ESM can be fundamentally different, the proposed simulations elucidate the uncertainties induced by unknowns in the climate changes for a given emission scenario.

Finally, our choice to invest in updating physics package in RACMO2 is based on the following rationale. For the research of the climate in Greenland and Antarctica, versatile RCMs still have an edge over ESMs, both due to the significantly lower costs of RCMs for equal resolution and due to their adaptivity to polar conditions. Even though non-hydrostatic RCMs and simulations on kilometres scale resolutions are increasing in number and quality, the numerical costs to run such simulations are still large in comparison to the available computational resources. Therefore, dedicated work on resolutions between 0.05 degree and 0.20 degree resolution for larger regional domains that cover Antarctica, the Greenland region or the Arctic will remain the scientific standard in the coming five to ten years. For this kind of work, a well-tuned polar-adapted non-hydrostatic model like RACMO2 is perfectly suitable.

Embedding

The proposed model runs will be of vital importance for several on-going and fully funded PhD and Postdoc projects at IMAU, Utrecht University. These PhDs and Postdocs will carry out the majority of the model simulations and the subsequent data analysis. The PI will manage the computing resources and will provide local support for running RACMO2. Erik van Meijgaard at KNMI will provide additional model support for RACMO2. The upgrade to RACMO2.4p1 will be carried out by a Postdoc in close collaboration with Erik van Meijgaard and Bert van Ulft of the KNMI and model support from ECMWF.

Total requested computational requirements

Research question			HPCF (MSBU)	ECFS (TB)
1)	Operational simulations	GrIS:	0.5	2
		AIS:	0.5	3
2)	CMIP6 driven projections (1950-2014 reference + 2 x 2015-2100)	GrIS:	14.1	100
		AIS:	8.2	60
3)	Firn densification work	Bipolar:	3.0	10
4)	Testing and first evaluations RACMO2.4p1		0.5	5
Unforeseen & unplanned (HPFC) and ECFS data rollover from 2020			2.2	20
Total			30.0	200

References:

Banwell, A.F., D.R. MacAyeal and O.V. Sergienko, 2013: Breakup of the Larsen B Ice Shelf triggered by chain reaction drainage of supraglacial lakes, *Geoph. Res. Lett.*, **40**, 5872-5876.

Box, J.E., X. Fettweis, J.C. Stroeve, M. Tedesco, D.K. Hall, and K. Steffen, 2012: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, *The Cryosphere* **6**, doi: 10.5194/tc-6-821-2012.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Conford. S.L., D.F. Martin, A.J. Payne, E.G. Ng, A.M. Le Brocq, R.M. Gladstone, T.L. Edwards, S.R. Shannon, C. Agosta, M.R. van den Broeke, H.H. Heller, G. Krinner, S.R.M. Ligtenberg, R. Timmermann, and D.G. Vaughan, 2015: Century-scale simulation of the response of the West Antarctic Ice Sheet to a warming climate, *The Cryosphere*, **9**, 1579-1600.

DeConto, R.M., D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise, *Nature*, **531**, 591-597.

Fettweis, X., S. Hofer, U. Krebs-Kanzow, C. Amory, T. Aoki, C.J. Berends, A. Born, J.E. Box, A. Delhasse, K. Fujita, P. Gierz, H. Goelzer, E. Hanna, A. Hashimoto, P. Huybrechts, M.-L. Kapsch, M.D. King, C. Kittel, C. Lang, P.L. Langen, J.T.M. Lenaerts, G.E. Liston, G. Lohmann, S.H. Mernild, U. Mikolajewicz, K. Modali, R.H. Mottram, N. Niwano, B. Noël, J.C. Ryan, A. Smith, J. Streffing, M. Tedesco, W.J. van de Berg, M.R. van den Broeke, R.S.W. van de Wal, L. van Kampenhout, D. Wilton, B. Wouters, F. Ziemen, and T. Zolles, 2020: GrSMBMIP: Intercomparison of the modelled 1980–2012 surface mass balance over the Greenland Ice sheet, *The Cryosphere Discussions*, https://doi.org/10.5194/tc-2019-321.

Fürst, J.J., G. Durand, F. Gillet-Chaulet, L. Tavard, M. Rankl, M. Braun and O. Gagliardini, 2016: The safety band of Antarctic ice shelves, *Nature Climate Change*, **6**, 479-482.

IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Jakobs, C.L., C.H. Reijmer, P. Kuipers Munneke, G. König-Langlo and M.R. van den Broeke, 2019: Quantifying the snowmelt-albedo feedback at Neumayer Station, East Antarctica, *The Cryosphere*, **13 (5),** 1473-1485.

Lenaerts, J.T.M., J.H. van Angelen, M.R. van den Broeke, A.S. Gardner, B. Wouters and E. van Meijgaard, 2013: Irreversible mass loss of Canadian Arctic Archipelago glaciers, *Geophys. Res. Lett.*, **40**, 1-5, doi:10.1002/grl.50214.

Ligtenberg, S.R.M., P. Kuipers Munneke, B.P.Y. Noël and M.R. van den Broeke, 2018: Brief communication: Improved simulation of the present-day Greenland firn layer (1960-2016), *The Cryosphere*, **12**, 1643-1649.

Mankoff, K.D., W. Colgan, A. Solgaard, N.B. Karlsson, A.P. Ahlstrøm, D. van As, J.E. Box, S.A. Khan, K.K. Kjeldsen, J. Mouginot, and R.S. Fausto, 2019: Greenland Ice Sheet solid ice discharge from 1986 through 2017*, Earth Syst. Sci. Data,* **11**, 769-786, https://doi.org/10.5194/essd-11-769-2019.

Mottram, R., N. Hansen, C. Kittel, M. van Wessem, C. Agosta, C. Amory, F. Boberg, W.J. van de Berg, X. Fettweis, A. Gossart, N.P.M. van Lipzig, E. van Meijgaard, A. Orr, T. Phillips, S. Webster, S.B. Simonsen, and N. Souverijns, 2020: What is the Surface Mass Balance of Antarctica? An Intercomparison of Regional Climate Model Estimates, *The Cryosphere Discussions*, https://doi.org/10.5194/tc-2019-333.

Noël, B.P.Y., W. J. van de Berg, H. Machguth, S. Lhermitte, I. Howat, X. Fettweis and M. R. van den Broeke**,** 2016: A daily, 1 km resolution data set of downscaled Greenland ice sheet surface mass balance (1958–2015), *The Cryosphere,* **10**, 2361-2377, doi:10.5194/tc-10-2361-2016.

Noël, B.P.Y., W.J. van de Berg, S. Lhermitte, B. Wouters, H. Machguth, I. Howat, M. Citterio, G. Moholdt, J.T.M. Lenaerts and M.R. van den Broeke, 2017: A tipping point in refreezing accelerates mass loss of Greenland's glaciers and ice caps, *Nature Communications,* **8**, doi: 10.1038/ncomms14730.

Noël, B.P.Y., W.J. van de Berg, S. Lhermitte and M.R. van den Broeke, 2019: Rapid ablation zone expansion amplifies north Greenland mass loss, *Science Advances,* **5 (9)**, DOI: 10.1126/scieadv.aaw0123.

Steger, C.R., C.H. Reijmer and M.R. van den Broeke, 2017: The modelled liquid water balance of the Greenland Ice Sheet, *The Cryosphere*, **11**, 2507-2526.

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

The IMBIE team, including M.R. van den Broeke, B.P.Y. Noël, W.J. van de Berg and J.M. van Wessem**,** 2020: Mass balance of the Greenland Ice Sheet from 1992 to 2018, *Nature*, **579**, 233-239.

Van Dalum, C.T., W.J. van de Berg, S. Lhermitte and M.R. van den Broeke, 2020: Evaluation of a new snow albedo scheme for the Greenland ice sheet in the regional climate model, The Cryosphere Discuss., https://tc.copernicus.org/preprints/tc-2020-118/, in review.

Van den Broeke, M.R**.**, E.M. Enderlin, I.M. Howat, P. Kuipers Munneke, B.P.Y. Noël, W.J. van de Berg, E. van Meijgaard and B. Wouters, 2016: On the recent contribution of the Greenland ice sheet to sea level change, *The Cryosphere,* **10**, 1933-1946, doi:10.5194/tc-10-1933-2016.

Van Wessem, J.M., W.J. van de Berg, B.P.Y. Noël, E. van Meijgaard, C. Amory, G. Birnbaum, C.L. Jakobs, K. Krüger, J.T.M. Lenaerts, S. Lhermitte, S.R.M. Ligtenberg, B. Medley, C.H. Reijmer, K. van Tright, L.D. Trusel, L.H. van Ulft, B. Wouters, J. Wuite and M.R. van den Broeke, 2018: Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 2: Antarctica (1979-2016), *The Cryosphere*, **12**, 1479-1498.

Zelinka, M.D., T.A. Myers, D.T. McCoy, S. Po-Chedley, P.M. Caldwell, P. Ceppi, S.A. Klein and T.E. Taylor, 2020: Causes of higher climate sensitivity in CMIP6 models, *Geophys. Res. Lett*., **47**, e2019GL085782.