REQUEST FOR A SPECIAL PROJECT 2022–2024

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. Peter Kuipers Munneke, Dr. Christiaan van Dalum, Dr. Carleen Reijmer, Max Brils MSc, Maurice van Tiggel MSc en, Sanne Veldhuijsen MSc (IMAU/UU), Dr. Erik van Meijgaard (KNMI)

Project Title:

High resolution regional modelling of contemporary and future polar climate and ice sheet surface mass balance

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SPNLBERG**	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2022	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2022-2024: (To make changes to an existing project please submit an amended version of the original form.)		**2022**	**2023**	**2024**
High Performance Computing Facility	(SBU)	125.000.000		
Accumulated data storage (total archive volume)[2]	(GB)	400.000		

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: High resolution regional modelling of contemporary and future polar climate and ice sheet surface mass balance

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

To understand the dynamics of the numerous changes in the polar regions induced by global warming, e.g. melting ice sheets, decreasing sea ice cover, thawing permafrost, high-resolution process-oriented climate models are essential. Our research group at IMAU focuses on atmospheric processes and the atmosphere-surface interactions. In 2022, continuing our research of the past years and within the framework of two (and potentially upcoming) European H2020 projects (Protect, PolarRES), we plan to use the regional atmospheric climate models RACMO2 and HCLIM and the firn (multiyear snow) densification model IMAU-FDM. We request HPCF and storage facilities for the following experiments:

1. Renewing our operational estimate (1950-2022) at 5.5 km resolution for the Greenland Ice Sheet with RACMO2.4.
2. Creating a new operational estimate (1979-2022) at 11 km resolution for the Antarctic Ice Sheet with RACMO2.4.
3. Performing a simulation of the Arctic climate (1950-2022) at 11 km resolution with RACMO2.4
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 20th and 21st century using IMAU-FDM.

All experiments aim to improve our understanding of the polar climate and glacial mass balance. Experiments 1, 2 and 5 also help to refine estimates of the mass balance of the two ice sheets and their adjacent glaciers and ice caps, which is of great importance to predict global sea level rise.

Motivation

Even though the polar regions constitute the least inhabited regions of the world, the observed and projected polar climate changes have impacts worldwide. The amplified warming of the Arctic, mostly caused by increased loading of atmospheric water vapour, leads to reduced sea ice and seasonal snow cover, which induces a lower planetary albedo, further enhancing regional warming (Zhang *et al*., 2019; He *et al*., 2019). Thawing sub-Arctic permafrost may become a significant emitter of greenhouse gases, adding another highly uncertain positive feedback to global warming (Randers and Goluke, 2020). The Greenland and Antarctic Ice Sheets are increasingly losing mass due to atmospheric and oceanic warming (the IMBIE team, 2018; 2020). During the last decades, the contribution of the two ice sheets to sea level rise has increased substantially; in case of strong continued future warming, mass loss from the ice sheets likely will be the dominant cause of multi-metre global mean sea level rise (e.g. Edwards *et al*., 2021), endangering coastal communities and infrastructure worldwide. Detailed understanding, appropriate models and accurate reconstructions of the climate of the recent past and future are prerequisites for reliable long-term projections given a choice of mitigation scenarios. For this understanding and these reconstructions, using high-resolution regional climate models (RCMs) applied to the polar regions is crucial.

Our research group focuses, among other research themes, on the climate of the polar regions using a wide range of numerical models, backed by dedicated in situ observations and satellite remote sensing data. These models include the Community Earth System Model CESM2, dynamical ice sheet models like ANICE and CISM, RCMs like RACMO2 and firn densification models like IMAU-FDM. For the latter two types of models we request resources in this proposal.

With RCMs, we firstly aim to improve our understanding of various aspects of the polar climate, for example, the impact of clouds on melt (Noël *et al.,* 2019, Fig. 1) or the interaction between atmospheric conditions and snow properties on surface albedo (Van Dalum *et al.,* 2021). Secondly, we provide high-resolution estimates of the surface mass balance of the two ice sheets, which contribute to improved estimates of their mass balance, and moreover, improved understanding of the drivers of mass loss (e.g. the IMBIE team, 2018, 2020). Besides that, our climate and surface mass balance data are used by research groups worldwide and in numerous studies and publications. Lastly, we use RCMs to generate projections of the surface mass balance for various pathways, which are essential to determine the future mass loss and overall stability of both ice sheets (e.g. Noël *et al.*, 2021).

We employ firn densification models for two aims. Firstly, to study the evolution of the firn layer thickness due to changes in air content, and to explore how the variability in precipitation influences the height (volume) of ice sheets and ice shelves. We provide accurate estimates of this firn layer evolution, so that elevation changes observed by satellite altimetry can be attributed to firn processes, basal melting of marine-terminating glaciers and ice shelves or dynamic thinning (e.g. Schröder *et al.*, 2019). Secondly, projecting the firn layer evolution is essential to understand, e.g. the stability of ice shelves in a warming climate (Kuipers Munneke *et al.*, 2014).

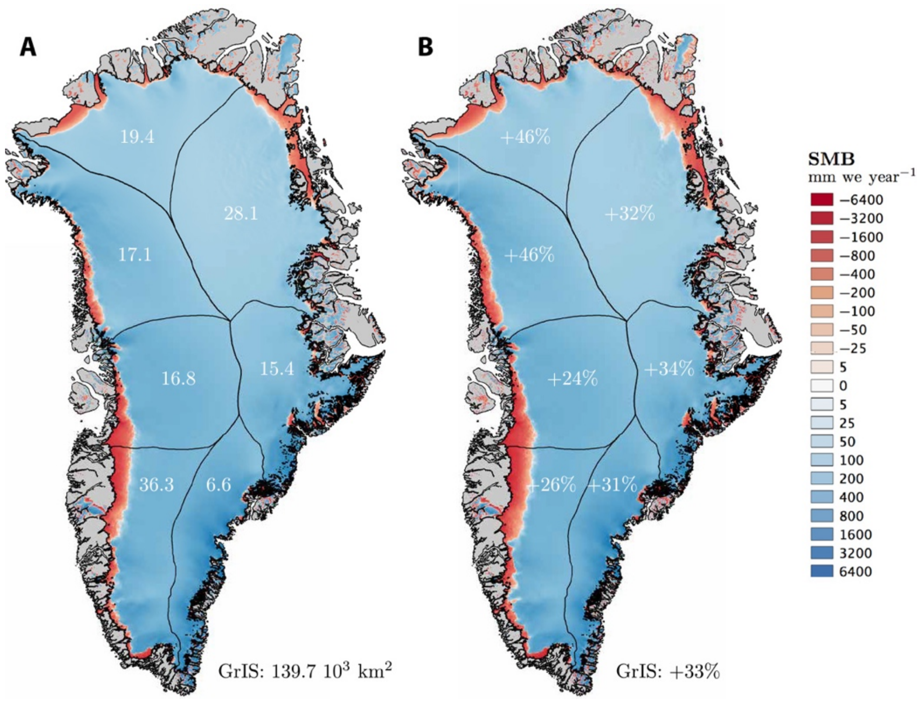

Figure 1: *Rapid ablation zone expansion enhances runoff contribution from north Greenland. (**A**) Map of SMB averaged for the period 1958–1990. Numbers refer to the ablation zone area for individual sectors (10^3 km^2) and for the whole Greenland Ice Sheet (bottom right). (**B**) Same as (A) for the period 1991–2017. Numbers refer to the relative ablation zone expansion (%) post-1990 for individual sectors and for the whole GrIS (bottom right). Figure taken from Noël et al., 2019.*

Methods

Prior to discussing the project rationales, we discuss the various models planned to be employed in 2022 within the special project resources.

RACMO2

The first RCM we are planning to use is the polar version of RACMO2. RACMO2 is one of the leading RCMs in this research field and has been used in hundreds of studies discussing the SMB and climate of the AIS, the GrIS and its peripheral glaciers, as well as other glaciated areas, e.g. the Canadian Arctic and Svalbard (e.g. Van Wessem *et al.*, 2018; Noël *et al.*, 2018; 2019; 2020). RACMO2 is a hydrostatic model, which makes the model suitable for the resolutions of the planned experiments (e.g. Van de Berg *et al.*, 2020) and less computationally expensive than non-hydrostatic models. RACMO2 has no dynamic ocean module, which is the logical set-up for RCM experiments over ice sheets.

In 2021 we commenced a major update of RACMO2 to version 2.4. The current operational version (2.3) employs ECMWF IFS physics cycle Cy33r1; we are updating RACMO2 to cycle Cy47r1. Besides numerous updates in the surface, turbulence, convection and radiation schemes, it will also introduce the newer cloud scheme with six prognostic hydrometeors, which is used in the IFS physics since cycle Cy36r4. We hope to see a major improvement in the description of the cloud phase over the ice sheets; due to low abundance of aerosols, liquid water clouds occur far more often than currently modelled by RACMO2. Furthermore, we expect an improvement in the horizontal distribution of precipitation, notably around rugged topography, as horizontal advection of precipitation is significant but was not modelled in IFS versions prior Cy36r4.

Given the obtained progress in embedding the new code into RACMO2, we expect to have the first working version of RACMO2.4 by the fall of this year. The next step is to embed the polar modifications of version 2.3 into 2.4, which is expected to take another 3 months. Another 3 months are planned for testing and tuning the polar version of RACMO2.4. Hence, the experiments proposed here are planned for spring 2022 or later, by which billing of computational time has resumed.

HCLIM

The second RCM we are planning to use is HCLIM38-ALARO, including the sea-ice model SICE (Belušić et al., 2020). HCLIM is the RCM version of the numerical weather prediction system ALADIN-HIRLAM. HCLIM38-ALARO is the convection permitting configuration of HCLIM. HCLIM has been applied over Europa as well as the Arctic region and Greenland.

Although the description of surface-atmosphere interactions over ice sheets in HCLIM is not yet optimized as in RACMO2, we foresee that in several years HCLIM will replace RACMO2. Firstly, HCLIM has the potential to deliver as accurate descriptions of the climate and surface mass balance of glaciers and ice sheets as RACMO2 currently does. HCLIM includes the SURFEX surface scheme, which has very detailed physical descriptions for glaciated surfaces. These descriptions, however, have not yet been used within the HCLIM framework. Secondly, the increasing computer power will progressively ease the efforts needed to accommodate the computational requirements of HCLIM. Lastly, this increasing computer power will allow higher resolutions for reanalyses and GCM simulations, reducing the added value of RCM simulations on 5 to 15-kilometre resolution.

IMAU-FDM

The last model we are going to use, is the 1-D firn densification model IMAU-FDM. Although RACMO2 includes similar physics as IMAU-FDM, the embedding within an RCM inhibits usage of numerous layers. IMAU-FDM uses the surface mass and temperature boundary conditions from RACMO2, however, IMAU-FDM maintains a vertical resolution of just several cm throughout the whole column, while in addition IMAU-FDM is run to pure steady state prior to the actual experiments. As a result, the modelled evolution of the firn layer with IMAU-FDM does not suffer from long term model drift and artificial trend breaks due to deep layer merging. In 2021, several parameterizations within IMAU-FDM were updated and this version is subsequently recalibrated for the Greenland and Antarctic Ice Sheet based on situ observations. This updated version will be used in 2022.

Proposed experiments for 2022

1. Using the updated polar version of RACMO2.4, we will renew our operational estimate of the climate and surface mass balance of the Greenland Ice Sheet. This simulation will be carried out at 5.5 km resolution; the surface mass balance fields will be subsequently statistically downscaled to 1 km resolution to better resolve the narrow marginal glacier tongues. The simulation will cover 1950 to 2022 and for this simulation, RACMO2.4 will be forced with ERA5 boundaries. After completion, the simulation will be regularly extended using ERA5T boundaries. For this experiment, we estimate a HPCF cost of 25 million SBU and a data storage of 76 TB.
2. Similarly, we will update our operational estimate for the Antarctic Ice Sheet. This simulation will be carried out at an unprecedented resolution of 11 km. The simulation will cover 1979 to 2022 and ERA5 boundaries will be used. The years prior 1979 are not modelled as for these years, reanalyses have too few observations over the Antarctic region to sufficiently constrain the past synoptic situation. After completion, the simulation will be regularly extended using ERA5T boundaries. This simulation is also part of our commitment to the H2020 funded project PolarRES. For this experiment, we estimate a HPCF cost of 17 million SBU and a data storage of 81 TB.
3. As part of our commitment to PolarRES, we complete a simulation of the Arctic region, following the CORDEX domain, at 11 km resolution. This simulation will extend from 1950 to 2022 and uses ERA5 boundaries. For this experiment, the estimated HPCF costs are 28 million SBU and requires 135 TB of storage space.
4. Furthermore, as part of our commitment to PolarRES, we will apply HCLIM38-SICE to a pre-determined coastal part of the Antarctic Ice Sheet, including a significant part of the adjacent continental shelf. The typical costs of an HCLIM simulation is 2 million SBU and 600 GB of storage space per model year. 2022, we expect to carry out about 20 model years, for which 40 million SBUs and 12 TB of storage space is needed.
5. Finally, as part of our commitment for the H2020 funded project Protect, we plan to renew our IMAU-FDM projections of the future evolution of the firn layer of the Greenland and Antarctic Ice Sheets. As boundary conditions, the CESM2 driven RACMO2 realisations following the RCPs SSP1-2.6 and SSP5-8.5 scenarios will be used. These RACMO2 experiments have been completed between 2019 and spring 2021. The combined estimated cost of these experiments is 10 million SBU and archiving requires 20 TB of storage space.

Applications and rationale

Various rationales justify the experiments proposed above.

As stated earlier, experiments 1 and 2 aim to provide as accurate as possible estimates of the contemporary climate, surface mass balance of the two ice sheets. Experiment 5 focus on their future firn state. With our past simulations we have reached these aims. Moreover, these data sets are shared with the scientific community without restrictions to facilitate further research; since January 2020 subsets of these data have been shared over 150 times. RACMO2 surface mass balance estimates are used in all major ice sheet mass balance studies, like the upcoming IPCC AR6 report, and RACMO2 data are used in numerous research papers. Since 2020 alone, tens of papers using RACMO2 data have been published, also in high-impact journals (e.g. Adusumili et al., 2020; Wood *et al*., 2020).

Experiment 3, a contemporary climate estimation for the Arctic region, aims to improve our understanding of atmosphere-land-sea ice-ocean processes in this region. RACMO2.4 is not particularly tailored for atmosphere-sea ice interaction nor a coupled atmosphere-ocean RCM, which is the case for leading Arctic RCMs. However, this simulation is part of the model ensemble of high-resolution Arctic climate realizations within the PolarRES project. This allows for a model intercomparison of the representation of, for example, polar clouds, the shallow stable boundary layer, albedo evolution as well as a model evaluation against the detailed observations carried out during the MOSAiC expedition (https://mosaic-expedition.org/, last access 29 June 2021).

Experiment 4, the HCLIM simulation for coastal Antarctica, is carried out within a joint effort to assess the realism of HCLIM results for the Antarctic region. Furthermore, a topographically complex coastal sector will be chosen, in order to derive a high-resolution estimation of the local precipitation patterns. Lastly, by enabling the SICE sea ice model, we plan to investigate the atmosphere-ocean surface interaction for the Antarctic region, which has currently received much less interest than in the Arctic.

Feasibility and embedding

The proposed experiments are challenging for several reasons.

Firstly, it requires a migration to the new ATOS system. However, as RACMO2, HCLIM and IMAU-FDM have been run on several different platforms before, this is not considered to become a significant issue.

Secondly, RACMO2.4 is not yet operational. Updating the IFS physics in RACMO2 to cycle Cy47r1 is a major technical challenge. However, eventually it is no more than combining two well tested models, and already major progress has been made in the past five months. Still, RACMO2.4 must first show a realistic representation of the polar climate and ice sheet surface mass balance prior to launching the proposed large experiments. We anticipate that several months will be required before the first RACMO2.4 results become available. If, however, RACMO2.4 is not timely available, the 11 km Antarctic and Arctic experiments can also be carried out with our current operational version RACMO2.3. More importantly, these experiments are part of the PolarRES project, for which two additional postdocs will be employed this fall to support our postdoc who is currently working on RACMO2.4.

The planned HCLIM simulation is also part of our PolarRES contribution. Therefore, we will have model support from KNMI, DMI, who will carry out similar HCLIM-SICE experiments for another Antarctic coastal zone, and MetNo, who will coordinate HCLIM activities within PolarRES.

Lastly, the IMAU-FDM experiments will be carried out by two PhD students as part of their research projects.

In brief, we request a large amount of resources to facilitate research projects of several postdocs and PhD students. The experiments are either continuations of ongoing research lines or otherwise very well embedded in (inter)national collaborations.

Overview of requested resources

Experiment	HPCF (million SBU)	Storage (TB)
1. Contemporary Greenland with RACMO2.4	25	76
2. Contemporary Antarctica with RACMO2.4	17	81
3. Contemporary Arctic with RACMO2.4	28	135
4. HCLIM-SICE for coastal Antarctica	40	12
5. Several bi-polar IMAU-FDM 21st century firn projections	10	20
Unforeseen, unplanned (HPCF); storage rollover from 2021	5	76
Total	**125**	**400**

References

Adusumilli, S., Fricker, H.A., Medley, B. *et al.,* Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves. *Nat. Geosci.* 13, 616–620, 2020.

Belušić, D., de Vries, H., Dobler, A., Landgren, O., Lind, P., Lindstedt, D., Pedersen, R. A., Sánchez-Perrino, J. C., Toivonen, E., van Ulft, B., Wang, F., Andrae, U., Batrak, Y., Kjellström, E., Lenderink, G., Nikulin, G., Pietikäinen, J.-P., Rodríguez-Camino, E., Samuelsson, P., van Meijgaard, E., and Wu, M.: HCLIM38: a flexible regional climate model applicable for different climate zones from coarse to convection-permitting scales, *Geosci. Model Dev*., 13, 1311–1333, https://doi.org/10.5194/gmd-13-1311-2020, 2020.

Edwards, T.L., Nowicki, S., Marzeion, B. *et al.* Projected land ice contributions to twenty-first-century sea level rise. *Nature* 593**,** 74–82, 2021.

Fettweis, X., et al., including B.P.Y. Noël, W.J. van de Berg and M.R. van den Broeke, GrSMBMIP: intercomparison of the modelled 1980–2012 surface mass balance over the Greenland Ice Sheet, *The Cryosphere*, 14, 3935–3958, https://doi.org/10.5194/tc-14-3935-2020, 2020.

He, M., Hu, Y., Chen, N. *et al.,* High cloud coverage over melted areas dominates the impact of clouds on the albedo feedback in the Arctic. *Sci Rep* 9, 9529, https://doi.org/10.1038/s41598-019-44155-w, 2019.

Kuipers Munneke, P., Ligtenberg, S., Van Den Broeke, M., & Vaughan, D., Firn air depletion as a precursor of Antarctic ice-shelf collapse. *Journal of Glaciology,* 60(220), 205-214. doi:10.3189/2014JoG13J183, 2014.

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

Noël, B., van de Berg, W. J., Lhermitte, S., Wouters, B., Schaffer, N., and van den Broeke, M. R., Six decades of glacial mass loss inthe Canadian Arctic Archipelago. *Journal of Geophysical Research: Earth Surface*, 123, 1430–1449, https://doi.org/10.1029/2017JF004304, 2018.

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, doi: 10.1126/sciadv.aaw0123, 2019.

Noël, B., Jakobs, C.L., van Pelt, W.J.J. *et al.,* Low elevation of Svalbard glaciers drives high mass loss variability. *Nat Commun* **11,** 4597 (2020). https://doi-org.proxy.library.uu.nl/10.1038/s41467-020-18356-1, 2020.

Noël B., L. van Kampenhout, J. T. M. Lenaerts, W. J. van de Berg and M. R. van den Broeke. A 21st century warming threshold for irreversible Greenland ice sheet mass loss, *Geophysical Research Letters*, 48(5), e2020GL090471, doi: 10.1029/2020GL90471, 2021.

Randers, J., Goluke, U. An earth system model shows self-sustained thawing of permafrost even if all man-made GHG emissions stop in 2020. *Sci Rep* 10, 18456, https://doi.org/10.1038/s41598-020-75481-z, 2020.

Schröder, L., Horwath, M., Dietrich, R., Helm, V., van den Broeke, M. R., and Ligtenberg, S. R. M.: Four decades of Antarctic surface elevation changes from multi-mission satellite altimetry, *The Cryosphere*, 13, 427–449, https://doi.org/10.5194/tc-13-427-2019, 2019.

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

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

Van de Berg, W. J., E. van Meijgaard, L. H. van Ulft, The added value of resolution in estimating the surface mass balance in southern Greenland, *The Cryosphere*, 14, 1809-1827, https://doi.org/10.5194/tc-14-1809-2020, 2020.

Van Dalum, C. T., Van de Berg, W. J., and Van den Broeke, M. R., Impact of updated radiative transfer scheme in RACMO2.3p3 on the surface mass and energy budget of the Greenland ice sheet*, The Cryosphere*, 15, 1823-1844, https://doi.org/10.5194/tc-15-1823-2021, 2021.

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, Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 2: Antarctica (1979-2016), *The Cryosphere*, **12**, 1479-1498, 2018.

Wood, M., E. Rignot, L. An, A. Bjørk, M. van den Broeke, C. Cai, I. Fenty, E. Kane, D. Menemenlis, R. Millan, M. Morlighem, J. Mouginot, B. Noël, B. Scheuchl, I. Velicogna, J. Willis and H. Zhang. Ocean forcing drives glacier retreat in Greenland, *Science Advances*, 7(1) : eaba728, doi : 10.1126/sciadv.aba7282, 2021.

Zhang, Unraveling driving forces explaining significant reduction in satellite-inferred Arctic surface albedo since the 1980s Rudong Zhang, Hailong Wang, Qiang Fu, Philip J. Rasch, Xuanji Wang, *Proceedings of the National Academy of Sciences*, 116 (48) 23947-23953; DOI: 10.1073/pnas.1915258116, 2019.