REQUEST FOR A SPECIAL PROJECT 2017–2019

MEMBER STATE: The Netherlands

Principal Investigator[1]: Dr. W. J. van de Berg

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

Address: Princetonplein 5

3584 CC, Utrecht

The Netherlands

E-mail: w.j.vandeberg@uu.nl

Other researchers: Brice Noël, Stan Jakobs, Melchior van Wessem, Leo van Kampenhout and Michiel van den Broeke (UU/IMAU)

Bert van Ulft and Erik van Meijgaard (KNMI, The Netherlands)

Project Title: Present and future climate of Antarctica and Greenland modelled with RACMO2.

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ________________	
Starting year: (Each project will have a well-defined duration, up to a maximum of 3 years, agreed at the beginning of the project.)	2017	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2017-2019: (To make changes to an existing project please submit an amended version of the original form.)		**2017**	**2018**	**2019**
High Performance Computing Facility	(SBU)	40.000.000		
Accumulated data storage (total archive volume)[2]	(GB)	210.000		

***An electronic copy of this form must be sent via e-mail to**:* *special_projects@ecmwf.int*

Electronic copy of the form sent on (please specify date):

……………………………………………

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 an annual progress report of the project's activities, etc.

[2] 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.

Principal Investigator: Dr. W. J. van de Berg, Utrecht University

Project Title: Present and future climate of Antarctica and Greenland modelled with RACMO2.

Extended abstract

It is expected that Special Projects requesting large amounts of computing resources (1,000,000 SBU or more) should provide a more detailed abstract/project description (3-5 pages) including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The Scientific Advisory Committee and the Technical Advisory Committee review the scientific and technical aspects of each Special Project application. The review process takes into account the resources available, the quality of the scientific and technical proposals, the use of ECMWF software and data infrastructure, and their relevance to ECMWF's objectives. - Descriptions of all accepted projects will be published on the ECMWF website.

Summary

Sea level rise due to significant mass loss from the Antarctic Ice Sheet (AIS) and the Greenland Ice Sheet (GrIS) is one of the largest threats of projected climate change. In the project proposed here, updated and improved estimates of the recent and future contribution of surface mass loss from the AIS and GrIS are provided using the regional climate model RACMO2. The proposed runs will provide new insights in the driving aspects of the surface mass balance of the AIS and GrIS, the role of melt water in the firn layer and the stability of the Antarctic ice shelves in the coming century.

Motivation

The AIS and GrIS are the two largest fresh water bodies on Earth and store a water volume equivalent to 56 and 7.3 m of global sea level rise, respectively. In the last decades, both ice sheets increasingly contribute to global sea level rise. For example, their combined contribution to global sea level rise has increased from about 0.28 mm a^{-1} for the period 1992-2000 to about 0.95 mm a^{-1} for 2005-2010 (Shepherd and others 2012), which is a very significant increase compared to the mean observed 1993-2010 global sea level rise of 3.2 mm a^{-1} (IPCC 2013). For the 21st century and beyond, even larger contributions of the GrIS and AIS to the global sea level are projected (e.g. Van Angelen and others, 2013; DeConto and Pollard, 2016), however with great uncertainty. For many low-lying countries and regions like The Netherlands or London, accurate global sea level rise projections are essential.

For the GrIS, enhanced ice melt is the primary cause for the recent enhanced mass loss (e.g. Enderlin and others, 2014). For the AIS, the recent mass loss is primarily due to enhanced ice discharge driven by ocean-ice sheet processes. Here, ice discharge into the ocean is strongly limited by ice shelves that provide buttressing. The stability of many Antarctic ice shelves and therewith grounded ice flow becomes marginal in a warmer future climate with significant snow melt (Kuipers Munneke and others, 2014; Trusel and others, 2015), potentially leading to even larger contributions of the AIS to future global sea level rise. In summary, understanding of the processes that govern melt and projections of future climate and snow and ice melt for the AIS and GrIS are indispensable for future sea level rise projections, and, eventually, for sustained flood security of several hundred million people.

Although several projections exist of future mass loss from the GrIS given an emission scenario, this future contribution is still uncertain because several positive and negative ice-sheet-surface – atmosphere feedbacks were not yet well modelled. In particular, these projections run short on modelling correctly the full firn layer that covers the ice, which is essential to assess the long-term response of the ice sheet to an increase of surface melt. Currently, the majority of the GrIS surface area is accumulation area and covered by a thick and cold firn layer. In a (much) warmer future, the whole of the current accumulation zone will observe regular to extensive surface melt. The cold and thick firn layer has the capacity to refreeze all the surface melt, and thus to limit the GrIS mass loss. However, if this refreezing capacity is lost, the GrIS will enter a state of irreversible deglaciation much sooner then if this refreezing capacity is preserved. A correct representation of the firn layer is similarly important for projections of future AIS mass loss: past disintegrations of ice shelves in Antarctica occurred once the firn layer had melted away.

Main research questions

We aim to answer the following research questions with the model simulations proposed below.

1) To which extent will refreezing mitigate future ablation of the Greenland Ice Sheet and its peripheral glaciers?

2) How much global warming can the AIS ice shelves stand before their stability becomes questionable?

Besides these questions concerning the future of the AIS and GrIS, we need to understand the response to the observed warming during the last few decades. Since ice sheet mass loss and firn column state can be measured by remote sensing, model simulations of the recent past are equally necessary for evaluation and uncertainty assessment.

Methods: RACMO2.3

As the current generation of global climate models (GCMs) show serious deficiencies in the representation of ice sheet surface – atmosphere interactions, and hence in estimating snow and ice melt, regional climate models (RCMs) are commonly used to model the surface mass balance (SMB) of the AIS and GrIS. We plan to use the Regional Atmospheric Climate Model RACMO2, which has been adapted to model the climate over ice sheets and has been used extensively before.

RACMO2 is a leading RCM in this research field, and has been used for numerous studies of the SMB and climate of the AIS and GrIS, as well as other glaciated areas like the Canadian Arctic and Patagonia (e.g. Noël and others, 2015; van Wessem and others, 2014; Lenaerts and others, 2013). RACMO2 is developed by the Royal Netherlands Meteorological Institute (KNMI) and consists of the dynamics of HIRLAM (version 5.0.6) and ECMWF IFS physics (version CY33R1). In order to represent the surface processes of glaciated areas, RACMO2 is extended with an interactive multi-layer snow model that includes heat conduction, firn densification, melt water percolation, retention and refreezing and snow grain evolution. Moreover, RACMO2 has a state-of-the-art snow albedo scheme depending on grain size and a parameterization of snowdrift. Recently, the performance of RACMO2 is improved by retuning snow albedo, snowdrift, firn densification and precipitation and cloud processes.

Like HIRLAM, RACMO2 is a fully parallel model with separated I/O and along with RACMO2 there is a suite of batch pre- and postprocessing scripts. RACMO2 is typically run on 300 to 700 cores (SMT) at ECMWF.

Runs to be performed

1) Greenland, present climate: a 1958-2016 run will be performed at 5.5 km resolution. This run is forced by subsequently ERA-40 and either ERA-Interim or ER5, if timely available. This RACMO2 run at 5.5 km resolution over Greenland costs approximately 19 kSBU per month, so the full run requires 14 MSBU and 50 TB storage space.

2) Greenland, future climate: one 1980-2100 run will be performed at 11 km resolution, as a 5.5 km simulation is too expensive for this longer time span. This simulation will be driven by CESM data, run for the 2.6 and RCP8.5 scenarios. Estimated costs are 3.9 kSBU per individual month thus 11,4 MSBU and 75 TB storage space for the full run.

3) Antarctica, present climate: a 1979-2016 run of whole Antarctica at 18 km resolution. ERA-Interim, or if timely available, ER5 boundaries will be used for this run. The runs will be initialized in 1979 as reanalysis data prior this date have shown to be of poorer quality for Antarctica and the Southern Ocean. The computing costs of this run are 5.0 kSBU per month, thus 2.2 MSBU and 15 TB of data for the whole run.

4) Amundsen Sea Sector (Antarctica), present climate: a 1979-2016 run of the Amundsen Sea Sector on 5.5 km resolution will be carried out. Figure 1, using results of a test run, shows the amount of detail in, for example, the precipitation field captured by RACMO2 on this high spatial resolution. As run #3, this run will be drive by ERA-Interim or ER5. The computing costs of this run are estimated on 11 kSBU per month, thus in total 4.9 MSBU and 18 TB of data.

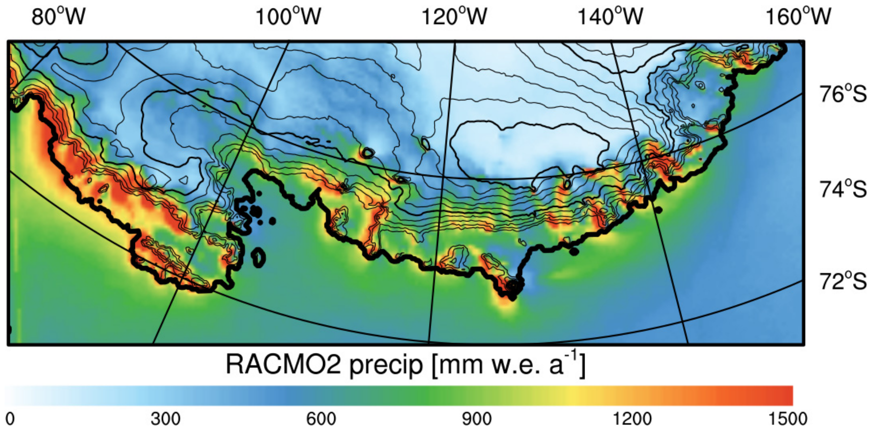

***Figure 1**: Modelled precipitation by RACMO2.3 for 1979 for the Amundsen Sea Sector, Antarctica. Clearly visible is the strong influence of promontories on the precipitation field, which is resolved on this high model resolution.*

5) Future climate: a 1979-2100 run for whole Antarctica on 27 km resolution, in which RACMO2 will be driven by CESM data, run with the RCP2.6 and 8.5 scenario. The estimated costs of this run are 6 MSBU, producing 50 TB of data.

Applications:

- Model output of the 1958-2016 5.5 km model simulation for the GrIS will be used to improve the ablation estimates from the lower GrIS ablation zone and the numerous peripheral glaciers. This high resolution is required because recent research has shown that 11 km resolution, which we have used so far, is insufficient to model the large SMB gradients in the narrow ablation zones of the GrIS (Noël and others, submitted) or the SMB of the numerous smaller glaciers on Greenland (Noël and others, in preparation). Pilot tests have shown that a doubling of resolution to 5.5 km will provide the required improvement in the representation of the land topography and glaciated areas needed for accurate SMB estimates for the GrIS and the peripheral glaciers (Figure 2). These results will be further refined using statistical downscaling to a 1 km product.
- The output of this 1958-2016 GrIS simulation will also be used to evaluate the firn model and in particular the long-term evolution of the firn layer in response to increasing surface melt.
- The output of GrIS future climate model run will be used to estimate future GrIS mass loss from ablation and the long term response of the firn layer in a warmer climate (research question 1).
- The output of AIS recent past climate model run will be used to evaluate the current model version for Antarctica and for mass balance studies of the AIS.
- The high-resolution run for the Amundsen Sea sector will be used to assess the current climate and firn layer state. Similar simulations on 5.5 km resolution have already been successfully completed for three other coastal regions in Antarctica: the Antarctic Peninsula, Dronning Maud Land and Victoria Land. The Amundsen Sea Sector is of high interest because the climate on the ice shelves is warmer than the average for the ice shelves of mainland Antarctica. The ice shelves in this sector in the current climate experience significant surface melt, but this melt is presently too weak to affect the integrity of the ice shelves. However, in a warmer climate melt most likely increases, which might start affecting the stability of the ice shelves in this region like melt caused the collapse of the Larsen B ice shelve in 2003.
- The high-resolution run for the Amundsen Sea sector will also be used to drive the ocean-sea ice model FESOM. This finite element ocean model includes explicit representation of the ocean circulation in cavities below the ice shelves and thus can explicitly model the sub shelf ice melt. High-resolution wind forcing, at the same resolution of the local resolution of FESOM, will likely improve the modelled coastal
- and sub-shelf ocean circulation as on this resolution, the sharp transition from katabatic winds over land to large-scale circulation driven winds over sea is resolved in detail.
- The output of the future climate run for Antarctica will be used to assess the future stability of the ice shelves (research question 2).
- Besides the applications listed above, the data will be used for numerous other applications and model output will be shared with the community.

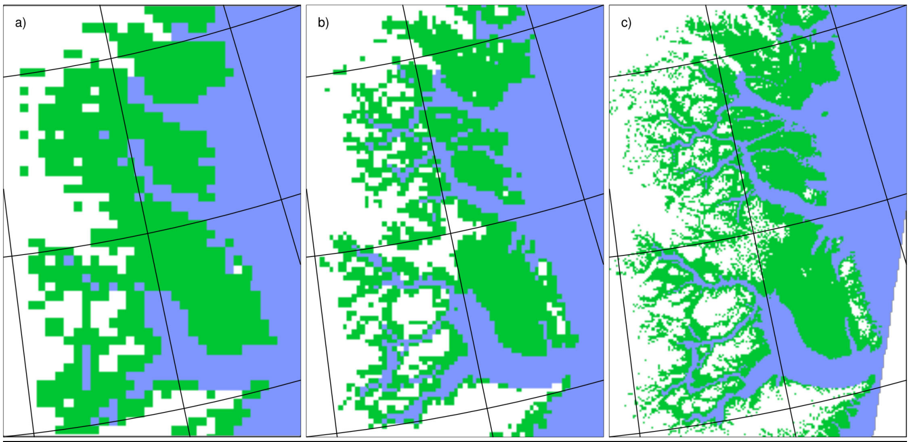

Figure 2: *Zoom of central east Greenland, highlighting how much better the complex topography is captured on a grid of 5.5 km compared to 11 km model grid. Glaciated area, land and sea points, in white, green and blue respectively, on* ***a)*** *11 km,* ***b)*** *5.5 km and* ***c)*** *1 km resolution.*

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 on RACMO2.3.

Total computational requirements

In total, we estimate to need 40 MSBU high performance computing facilities. In this request, 5% overhead is included for additional tests. As we are used to archive model output in detail, the data storage request is significant with 210 TB. This storage, however, is needed to allow detailed analysis of the model output in a later stage of the research.

References:

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

Enderlin, E. M., I. M. Howat, S. Jeong, M.-J. Noh, J. H. van Angelen, **and** M. R. van den Broeke**, 20**14: An improved mass budget for the Greenland ice sheet, *Geophysical Research Letters* **41**, 866–872, doi:10.1002/2013GL059010.

Kuipers Munneke, P, S.R.M. Ligtenberg, M.R. van den Broeke and D.G. Vaughan, 2014: Firn air depletion as a precursor of Antarctic ice-shelf collapse, *J. Glac*. **60**(220), 205-214.

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.

Noël, B., W.J. van de Berg, E. Van Meijgaard, P. Kuipers Munneke, R. S. W. Van de Wal, and M. R. Van den Broeke, 2015: Evaluation of the updated regional climate model RACMO2.3: summer snowfall impact on the Greenland Ice Sheet, *The Cryosphere* **9**, 1831-1844.

Shepherd, A. and 48 others (including W.J. van de Berg and M.R. van den Broeke) 2012: A Reconciled Estimate of Ice-Sheet Mass Balance, *Science* **338**, 1183-1189.

Trusel, L.D., K.E. Frey, S.B. Das, K.B. Karnauskas, P. Kuipers Munneke, E. van Meijgaard and M.R. van den Broeke, 2015: Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios, *Nature Geos*. **8,** 927-932.

Van Angelen, J. H., J. T. M. Lenaerts, M. R. van den Broeke, X. Fettweis and E. van Meijgaard, 2013: Rapid loss of firn pore space accelerates 21st century Greenland mass loss, *Geophys. Res. Lett*. **40**(1–5), doi:10.1002/grl.50490.

Van Wessem, J.M., C.H. Reijmer, J.T.M. Lenaerts, W.J. van de Berg, M.R. van den Broeke and E. van Meijgaard, 2014: Updated cloud physics in a regional atmospheric climate model improves the modelled surface energy balance of Antarctica, *The Cryosphere* **8**, 125-135.

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen and T. Zhang, 2013: Observations: Cryosphere. 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.