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Brief Communication: Upper air relaxation in RACMO2 significantly improves modelled interannual SMB variability in Antarctica

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Abstract

The regional climate model RACMO2 has been a powerful tool for improving SMB estimates from GCMs or reanalyses. However, new yearly SMB observations for West Antarctica show that the modelled interannual variability in SMB is poorly simulated by RACMO2, in contrast to ERA-Interim, which resolves this variability well. In an attempt to remedy RACMO2 performance, we included additional upper air relaxation (UAR) in RACMO2. With UAR, the correlation to observations is similar for RACMO2 and ERA-Interim. The spatial SMB patterns and ice sheet integrated SMB modelled using UAR remain very similar to the estimates of RACMO2 without UAR. We only observe an upstream smoothing of precipitation in regions with very steep topography like the Antarctic Peninsula. We conclude that UAR is a useful improvement for RCM simulations, although results in regions with steep topography should be treated with care.

1 Introduction

With an annual mass turnover equivalent to a 6 mm change in global sea level, the Antarctica Ice Sheet (AIS) plays an important role in sea-level change. The surface mass balance (SMB) and ice discharge determine the net mass change of the AIS. Recent satellite mass budget studies, e.g. Shepherd et al. (2012); Velicogna et al. (2014), show a large temporal variability in the AIS mass balance acting on monthly and decadal time scales. Although ice discharge can vary strongly on multi-year time scales, the SMB variability is responsible for most of the interannual variability in ice-sheet mass balance. Since AIS integrated SMB can not be measured remotely nor derived from in situ observations, the SMB and its variability must be derived from atmospherical modelling. Evaluation of the mean modelled SMB fields is possible (Favier et al., 2013; Van Wessem et al., 2014a), but until recently a direct evaluation of annual SMB has been impossible in absence of suitable observations. The newly developed

TCD
9, 4981–4995, 2015

technique of combining airborne radar with ice core data provides annual SMB estimates on the scale of a glacier catchment (Medley et al., 2013, 2014). These data provide new opportunities for evaluation of modelled SMB evaluation, specifically over the Thwaites Glacier catchment in West Antarctica.

The SMB can be resolved from reanalysis products like ERA-Interim, but regional atmospheric climate models driven by reanalyses outperform the reanalyses in representing the spatial patterns (e.g. Van de Berg et al., 2006; Lenaerts et al., 2012). Here, we use model data from the regional climate model (RCM) RACMO2, version 2.3 (Van Wessem et al., 2014a). Unless data assimilation is applied, a RCM cannot improve upon the reanalysis interannual variability because the variability is set by the large-scale circulation. RACMO2 in its default version neither has data assimilation nor relaxation to boundary conditions in the upper atmosphere. Hence, the free evolution of the model interior will partly remove the true interannual variability, deteriorating the correlation with observational time series. Therefore, we discuss whether relaxation to boundary conditions (nudging) is beneficial. This relaxation can be implemented by using spectral and indiscriminate nudging. In the case of indiscriminate nudging, model fields are adjusted to the boundary conditions without regard to any spatial scales and structures in the modelled deviations. As a result, modelled small scale patterns are partially suppressed because these patterns are absent in the coarser resolution boundary condition. Relaxation with spectral nudging circumvents smoothing of the model state because relaxation is applied in the spectral space, which allows for adjustment to only the longer wavelengths to the boundary conditions. Spectral nudging is thus potentially better than indiscriminate nudging, but it is computationally more expensive. Although applied on different geographical locations and meteorological conditions, several studies (e.g., Pohl and Crétat, 2014; Omrani et al., 2015) have shown that boundary relaxation improves the representation of the surface climate and precipitation fields. These studies show that the wind and temperature fields are the most important fields to constrain by nudging and that spectral and indiscriminate nudging both improve the representation of the modelled fields.

TCD
9, 4981–4995, 2015

In this study, we applied upper air relaxation (UAR), which is indiscriminate nudging applied on the upper part of the atmosphere only. Indiscriminate nudging is justifiable because the upper atmosphere only is gently stirred towards the boundary fields. In this manner, UAR aims to retain the improved spatial patterns provided by a RCM but also the resolved interannual variability of ERA-Interim.

2 Model, methods and observations

2.1 RACMO2

The Regional Atmospheric Climate Model RACMO2 has been used for over a decade to estimate the climate and SMB of Antarctica. RACMO consists of the dynamics of the RCM HiRLAM, the physics package of the ECMWF IFS model and a multi-layer snow model including grain size dependent albedo and snow drift. Here, we use RACMO version 2.3, which has been described and evaluated in detail for Antarctica by Van Wessem et al. (2014a, b). We compare the simulation presented by Van Wessem et al. (2014a) with ERA-Interim (Dee et al., 2011) and an additional simulation using UAR. Both RACMO2 simulations employ an identical domain and code except for the UAR and both were driven by ERA-Interim and run from 1979 to 2013. The simulation domain has a resolution of 27 km, utilizes 40 vertical levels, and extends well outside Antarctica.

2.2 Upper air relaxation (UAR)

The default version of RACMO2 is adjusted only at its lateral boundaries to weather fields from the driving global model. The interior of the domain is allowed to evolve freely, hence, no nudging is applied to the weather over Antarctica. This freedom is reduced if indiscriminate UAR is applied. In that case, the upper part of the modelled atmosphere is weakly relaxed to the ERA-Interim fields.

TCD
9, 4981–4995, 2015

This relaxation is implemented in the following manner and is only applied on temperature and wind fields. The relaxation uses the scaled, terrain-following σ coordinate which ranges from 0 (zero air pressure) to 1 (at the earth surface). Every time step, a model value (Φ) at location ($\boldsymbol{x} = \{x, y, \sigma\}$) is adjusted to the driving fields using

$$\Phi(\boldsymbol{x}) = (1 - \lambda_\tau \lambda_\sigma(\sigma))\Phi(\boldsymbol{x})_\mathrm{R} + \lambda_\tau \lambda_\sigma(\sigma)\Phi(\boldsymbol{x})_\mathrm{B}, \quad (1)$$

where $\Phi(\boldsymbol{x})_\mathrm{R}$ and $\Phi(\boldsymbol{x})_\mathrm{B}$ are the specific values from RACMO2 and the boundary fields, respectively, valid for that location and time step. If $\boldsymbol{x}$ is located in the boundary relaxation zone, the boundary relaxation is applied additively on Eq. (1).

A relaxation time scale (τ) of 6 h is applied, so for a model time step (t_R) of 600 s, λ_τ, defined as

$$\lambda_\tau = 1 - \frac{1}{\exp(t_\mathrm{R}/\tau)},$$

is 0.027. The vertical relaxation coefficient $\lambda_\sigma(\sigma)$ is defined with

$$\begin{aligned} \sigma \le 0.6: &\quad \lambda_\sigma(\sigma) = (1 + \cos(\sigma\pi/0.6))/2 \\ \sigma \ge 0.6: &\quad \lambda_\sigma(\sigma) = 0. \end{aligned} \quad (2)$$

Figure 1 shows the values of σ and λ_σ as function of the pressure and elevation for a site at sea level and 2000 and 4000 m a.s.l. This function allows a gradual stronger relaxation with elevation without sharp gradients. Using of the terrain-following coordinate ensures that the near-surface fields are never relaxed to the driving fields.

2.3 Radar observations in West Antarctica

For the evaluation of interannual SMB variability, we use airborne radar observations made in the Thwaites Glacier catchment (Fig. 2). The data and retrieval method are discussed in detail in Medley et al. (2013). In brief, the snowradar tracks radar reflection layers along flight lines that are dated using firn cores drilled at strategic locations

TCD
9, 4981–4995, 2015

along the flight lines. Using radar wave propagation and firn compaction modelling, the retrieval time difference between reflection layers is converted into annual accumulation.

3 Results

3.1 Evaluation of mean SMB and climate

First, the mean 1979–2013 SMB modelled by RACMO2 including UAR is compared to the reference model version. Figure 3 shows that large scale SMB patterns are largely unchanged, the differences are typically less than 10 % of the reference value. Integrated over the grounded ice sheet, the mean annual SMB decreases by 80 $\mathrm{Gt\,a^{-1}}$ (4 %) to 1979 $\mathrm{Gt\,a^{-1}}$. Some areas along the coast receive more mass, but in general precipitation and subsequently SMB decrease. This decrease is related to a small increase of upper air temperature without an equivalent increase of absolute humidity. For example, the 500 hPa temperature (not shown) increases above Antarctica by 0.2 to 0.6 K while the relative humidity decreases by 0 to 2 %.

3.2 Interannual variability

In Fig. 4, the integrated annual SMB derived from observations, ERA-Interim, and the two RACMO2 runs is displayed. The ERA-Interim SMB, derived from precipitation minus sublimation, is systematically lower the the observed SMB, due to underestimated precipitation. The ERA-interim correlation with observed interannual variability, however, is high. With $r = 0.93$, 87 % of the interannual variability is explained by the ERA-Interim. The reference RACMO2 simulation provides a large improvement on the mean SMB: RACMO2 is on average less than 2 % drier than observed. Much of the representation of the interannual variability is lost: the range is comparable but the correlation ($r = 0.69$) has deteriorated. A closer inspection of Fig. 4 shows that model deviations have an episodic nature. For example, the 1985–1991 SMBs are well modelled, then the reference model output deviates for 3 subsequent years. Hence, lateral boundary conditions only do not provide enough constraints for RACMO2 to reproduce day-to-day weather patterns for some years, but for some years it does. This intermittent model drift is removed in the UAR simulation, which combines the best of both the reference run and ERA-Interim. The mean SMB remains well modelled although the dry bias has increased to 5.5 %. This new simulation, however, reproduces 83 % ($r = 0.91$) of the observed variability, a similar correlation with observations as the ERA-Interim.

3.3 Regional patterns

Since ERA-Interim has a native resolution of 0.75°, UAR dampens small scale upper air structures in the RCM. Mesoscale topographic features like the Antarctic Peninsula are much better resolved in RACMO2 than in ERA-Interim. As a result, for the ERA-Interim fields that are fed into RACMO2, the topographic effect on the circulation in the free atmosphere extends over a much larger area than RACMO2. UAR thus introduces topographic effects at locations where they are not modelled by RACMO2. This artefact affects the precipitation fields modelled on, for example, the Antarctica Peninsula (AP) as shown in Fig. 5. In the adjusted simulation, orographic precipitation is modelled for a much wider area than the AP alone, leading to a decrease of precipitation on the mountain range itself. Although temperature and humidity fields also show small scale disturbances around the AP, the upper air wind field is the driving component. Prescribed orographical divergence of the upper air flow enhances upward motion west of the AP, while on the spine of the AP, UAR reduces the orographical driven vertical motion. An additional test, in which UAR was applied on the wind fields only, shows a similar dispersion of precipitation as the normal UAR simulation. We, therefore, conclude the topographic convergence and divergence of wind fields as prescribed by ERA-Interim affects the precipitation fields over the AP. The limited amount of SMB observations and the high spatial variability of SMB across the AP inhibit evaluation of the model results. Nevertheless, we assess that this dispersion of precipitation is

TCD
9, 4981–4995, 2015

likely a deterioration of the precipitation fields, since in general RACMO2 has a better representation of spatial precipitation patterns than ERA-Interim.

4 Discussion and conclusions

In this manuscript, we show the potential of upper air relaxation to improve the representation of interannual variability in regional climate models over Antarctica, specifically, RACMO2. For this study, we used the regional climate model RACMO2 and the reanalysis ERA-Interim. With this method, the modelled interannual variability closely resembles the variability ERA-Interim, which reproduces the variability in the observations well. RACMO2 still largely improves the representation of the spatial patterns and total mass flux as compared to ERA-Interim. Nevertheless, a smoothing of precipitation fields is observed, mostly over very steep topography. This effect is induced by the prescribed upper air winds, leading to extended regions of forced large scale precipitation. Upper air relaxation is thus not an ideal method for rugged regions. In those regions, spectral nudging, which only adjust the larger spatial scales in weather patterns, might be a better approach. Although not demonstrated with runs using other reanalyses or GCM boundaries, we believe that these conclusions are general valid for using UAR.

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TCD
9, 4981–4995, 2015

Brief Communication: Upper air relaxation in RACMO2

W. J. van de Berg and B. Medley

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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TCD

9, 4981–4995, 2015

Brief Communication: Upper air relaxation in RACMO2

W. J. van de Berg and B. Medley

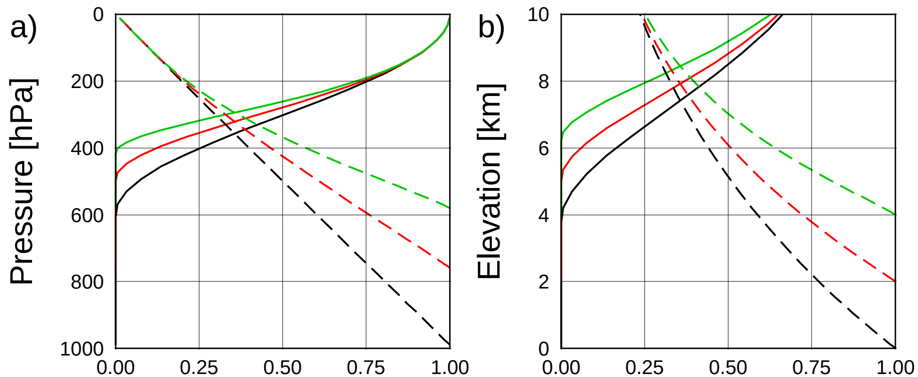

Figure 1. $\lambda_\sigma(\sigma)$ (solid lines) and σ (dashed lines) as function of **(a)** pressure and **(b)** elevation for a location at 0 (black lines), 2000 (red lines) and 4000 (green lines) m a.s.l., respectively.

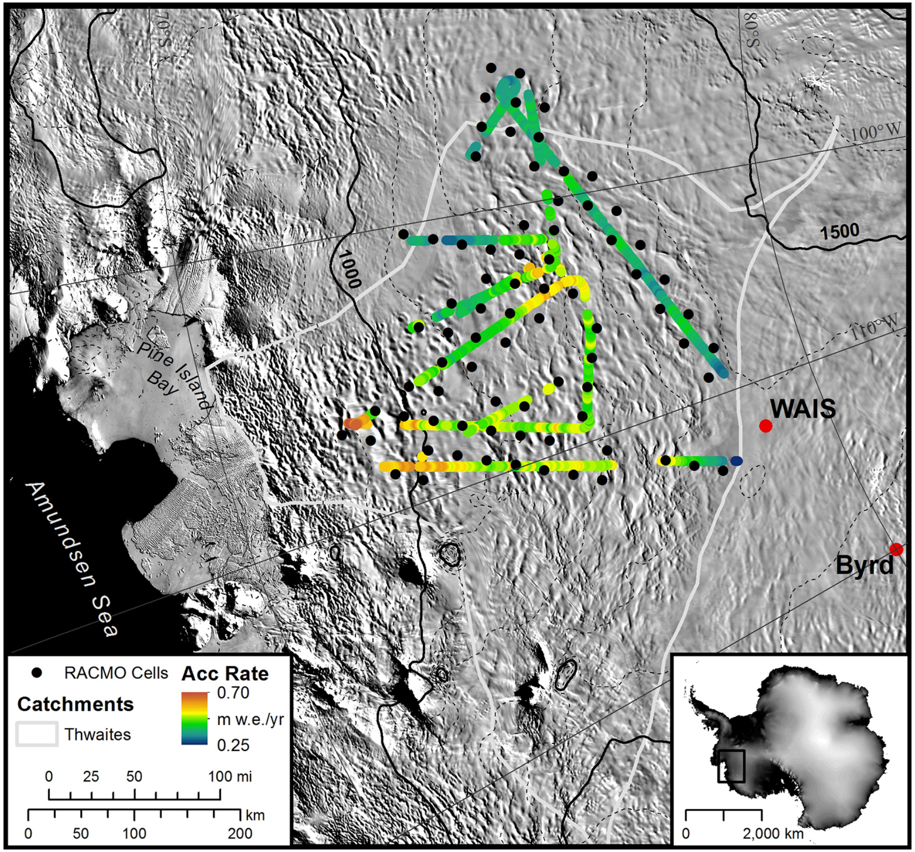

Figure 2. Map of the study area, including catchment delineation (white line), elevation contours (black lines), radar-derived SMB and the location of the RACMO grid points used for comparison (black dots). The background image is de MODIS Mosaic of Antarctica (Scambos et al., 2007).

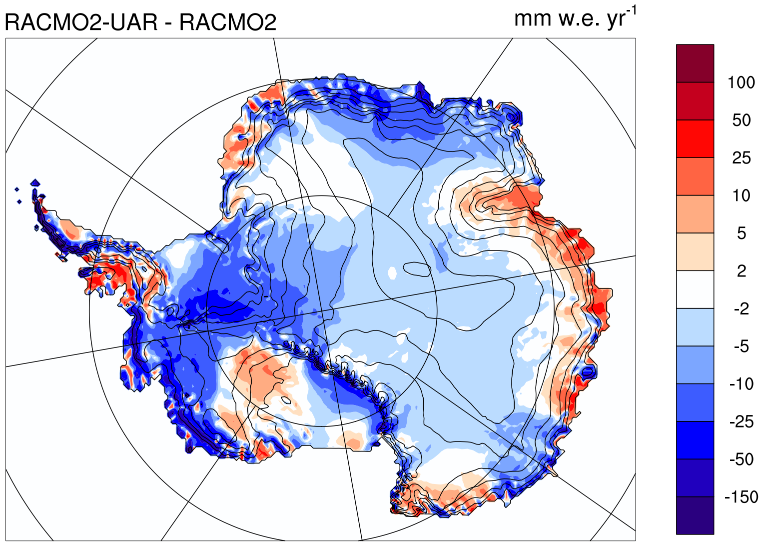

Figure 3. Difference in SMB between the UAR and reference RACMO2 simulation for 1979–2013.

TCD
9, 4981–4995, 2015

Brief Communication: Upper air relaxation in RACMO2

W. J. van de Berg and B. Medley

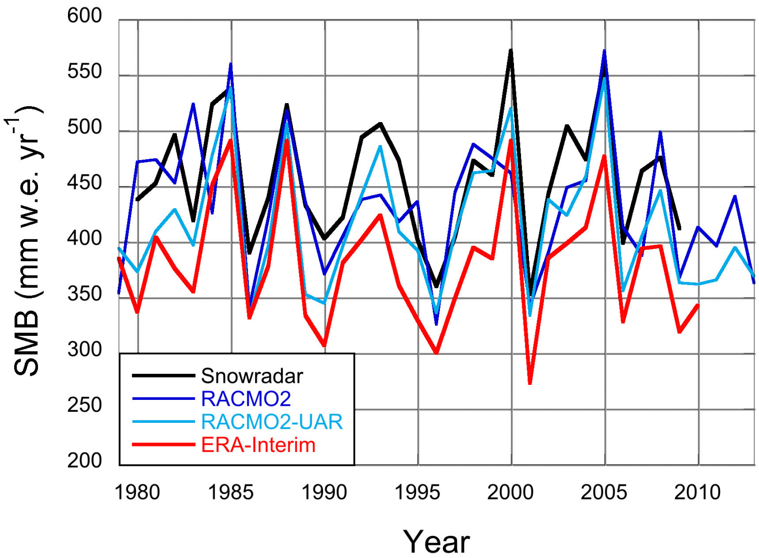

Figure 4. Observed and modelled integrated annual SMB.

TCD
9, 4981–4995, 2015

Brief Communication: Upper air relaxation in RACMO2

W. J. van de Berg and B. Medley

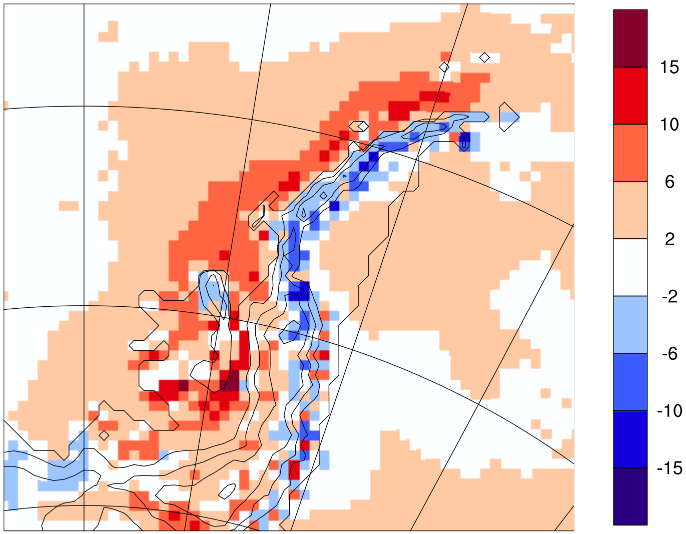

Figure 5. Relative difference [%] in precipitation between the UAR simulation and the reference RACMO2 simulation over the Antarctic Peninsula.

TCD
9, 4981–4995, 2015