Author responses to the reviewer comments on

Brief Communication: Upper air relaxation in RACMO2 significantly improves modelled interannual surface mass balance variability in Antarctica

by

W. J. van de Berg and B. Medley

First of all, we thank the reviewers for their time and their constructive comments. Here we address these comments point by point.

Reviewer #1 (Xavier Fettweis)

RC#1: As the authors know, we use the same technique in the regional model MAR to prevent MAR to simulate its own general circulation when the integration domain is very large like Antarctica. However, our upper nudging is limited to the stratosphere (> 10 km (250hPa, σ < 0.25) above the topography) to prevent the large scale forcing to impact the precipitation processes in MAR. Here, the relaxation in RACMO starts at ~ 5 km (500hPa, σ < 0.6) above the surface and therefore impacts the precipitation simulated by RACMO as shown by the authors (Precipitation discrepancies could also be due to differences in the general circulation simulated by RACMO). Are there some justifications to start the relaxation zone at σ = 0.6? Lower sigma values have been tested? It should be interesting to show the impact of the vertical relaxation coefficient distribution to precipitation by re-simulating one year only.

AC: Admittedly, we did not implement upper air relaxation (UAR) with the intent to improve the representation of interannual variability over Antarctica. It was implemented to constrain RACMO2 to a realistic climate if run over a much larger domain covering the Southern Hemisphere up to ~35 °S. In that framework, we optimized σ and the relaxation timescale to find trade-off between RCM freedom and reproducing the right surface climate (e.g. surface pressure). We chose σ =0.6 because lower values of σ leaded to too much model drift.

These model settings were next applied on our normal domain for Antarctica to test if UAR affects the modeled surface climate. These results are presented in the manuscript. So, we did not test different values of σ for this domain and purpose. On suggestion of the reviewer, we reran RACMO with σ = 0.25 and a time scale of 6 hours. However, since one month or year does not show whether σ = 0.25 is an alternative, we have made this test longer.

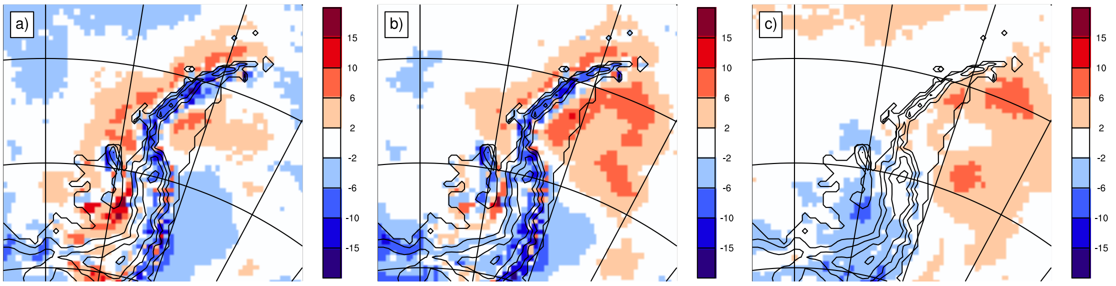


***Figure 1**: Relative change of precipitation for 1979-1993 for **a)** σ = 0.6, **b)** σ = 0.25. **c)** Difference between b) and a).*

Figure 1 shows that starting UAR at a higher elevation does not reduce the precipitation dispersion. On the other hand, the correlation with observations strongly deteriorates. There is thus no advantage in starting constraining the circulation at a higher point in the atmosphere.
We added this sensitivity test in the section 3.3 P7 L23:
"A second test, in which only the stratosphere was constrained, i.e. relaxation for $\sigma \leq 0.25$ (Eq. 2), showed no improvement of the patterns over the AP while the correlation of modelled SMB with snow radar data for Thwaites glacier basin clearly deteriorated."

RC #2 Using UAR impacts firstly the general circulation simulated by RACMO. Are there significant differences between the mean Z500 simulated by RACMO with and without UAR? With ERA-Interim? To show the interest of using UAR, comparison with daily surface pressure observed in the centre of the integration domain (or from ERA-Interim) helps also to show the impact of using UAR to the general circulation simulated by RACMO. If it is not a big job for the authors, I recommend to add a short paragraph discussing more in depth the impact of UAR to the general circulation simulated by RACMO.

AC: As mentioned in the manuscript, the mean general circulation hardly changes. Since a brief comment has a very limited number of figures (officially 3), we still would like to leave out all figures that show the changes in upper air circulation – since those changes are small. For your convenience we have included them here in Figure 2.

Also for surface pressure the effect of UAR on the modeled climate is limited. As shown in Figure 3, the mean surface pressure between the unconstrained reference run and the constrained UAR run is less than 0.7 hPa, leaving circulation patterns unaffected. The additional constraint from UAR slightly reduces the daily variability. Finally, as expected, the constrained and unconstrained run starts to deviate away from the margins; nevertheless, the correlation never gets below 0.8.

In order to address to the reader more clearly that the mean climate modeled by RACMO2 is largely unchanged, we replaced lines 101-102 by
"At the 500 hPa level, temperatures (not shown) increase above Antarctica by 0.2 to 0.6 K while relative humidities decrease by 0 to 2%. All in all, the difference in the modeled mean climate between the reference and UAR runs is very limited. For example, mean surface pressures and 2 m temperatures differ only at max 0.7 hPa and 0.6 K, respectively."

Minor marks:
Definitions of SMB, RCM and ECMWF IFS are added; SMB in the title is replaced by surface mass balance.

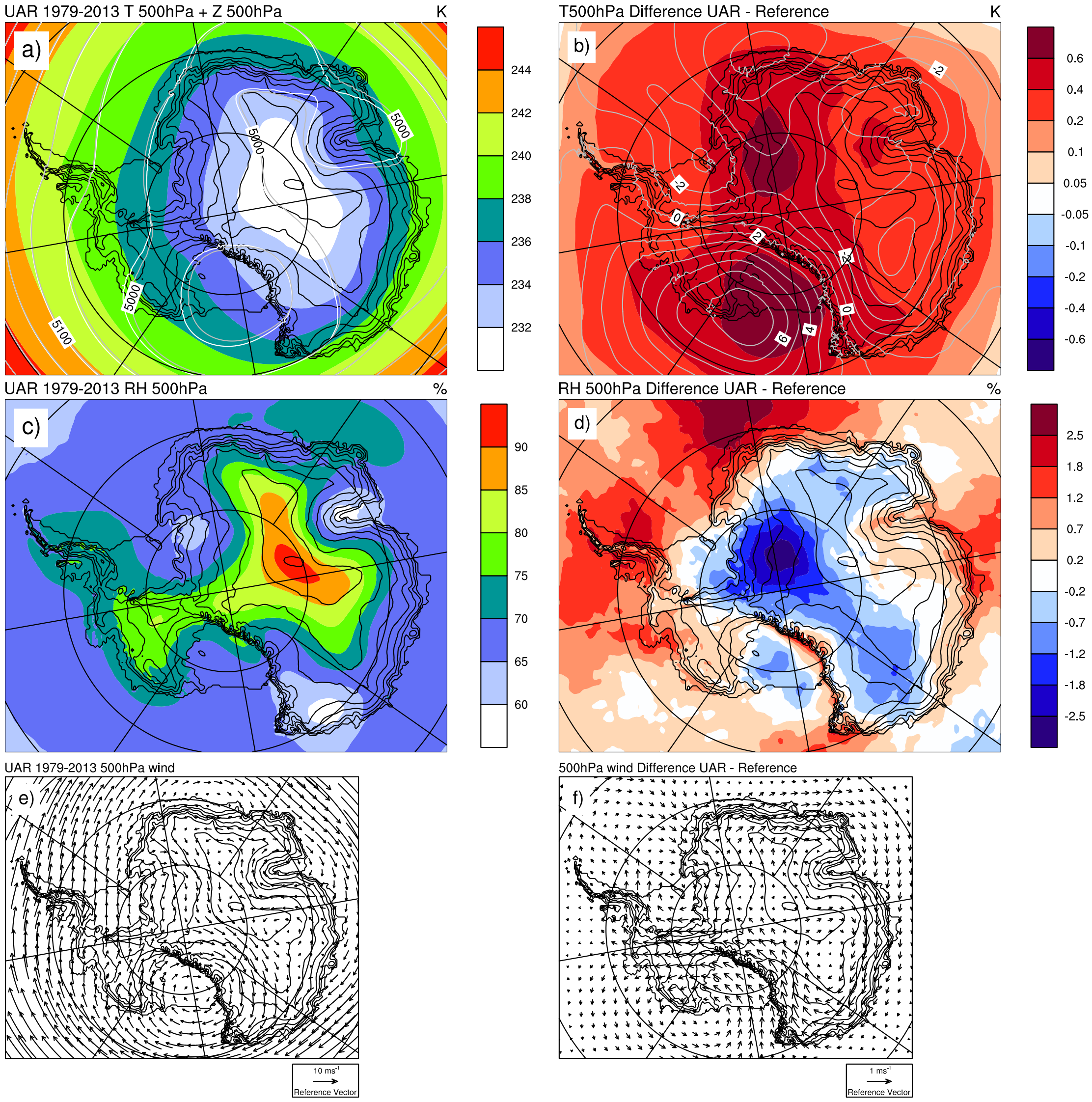


***Figure 2**: 1979-2013 500 hPa **a)** Temperature (colors) and elevation (grey lines), **c)** relative humidity and **e)** winds modeled by RACMO with using UAR. The difference between the UAR and reference simulation is given in figures **b)**, **d)** and **f)**. In figure a), Z 500hPa from the reference run is drawn in white.*

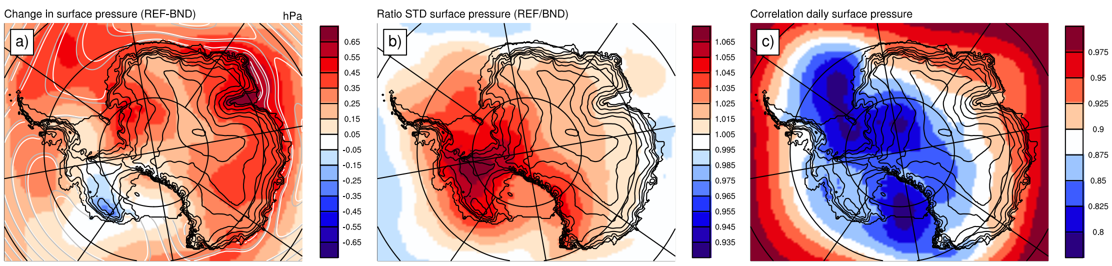


Figure 3: **a)** mean difference in surface pressure. Over sea, isobars are drawn every 2 hPa with the reference run and UAR run in white and grey, respectively. **b)** Ratio of the standard deviation of daily surface pressure. **c)** Correlation between daily surface pressures. All plots used data from 1979-2013.

Reviewer #2:
Comments not listed below are adjusted as suggested.

RC P3, l9: I can envisage situations where interannual variability might be better represented in a RCM even without data assimilation. For example, in regions where accumulation is dominated by orographic precipitation over small-scale topography (which would not be resolved in the driving model).
AC: Even for that case we doubt if a RCM would improve the interannual variability since the latter is still largely determined by large-scale patterns. Nevertheless, we can't exclude this possibility so we rephrased the sentence to:
"Over Antarctica, where the variability is set by the large-scale circulation, a RCM will unlikely improve upon the reanalysis interannual variability unless data assimilation is applied."

RC P3, l11 (and elsewhere): To avoid confusion, I would say "relaxation to large-scale forcing fields", rather than "relaxation to boundary conditions". The latter is what you are doing at the lateral boundaries of the model domain while the former describes the nudging process.
AC: Adjusted as suggested, also elsewhere.

RC P5, l1 (see also section 3.1): Why did you choose not to nudge moisture fields? Nudging T but not q has clearly had an impact on precipitation as it changes the relative humidity field.
AC: We excluded humidity fields because we expected that relaxing humidity fields would strongly interfere with the cloud and precipitation parameterizations in RACMO2. Clouds contain a limited fraction of the available water vapor, and precipitative processes can reduce the cloud content rather quickly. Moisture processes near the saturation point are thus very subtle to model and vary from model to model and model version to model version. Relaxing humidity would have a large impact on cloud cover and would lead to incidental excessive precipitation as we observe that in the boundary relaxation zone. Here, we prescribe humidity, which leads to strongly enhanced precipitation rates. We added at this point the following sentence:
"Humidity fields are not relaxed because that would lead to undesired distortions to the modeled clouds and precipitation fluxes, as already observed in the lateral boundary relaxation zones."

RC P6, section 3.2: It might be useful to include a short table that summarises the key metrics (correlations, mean and RMS differences) from figure 4?
AC: A table is added:

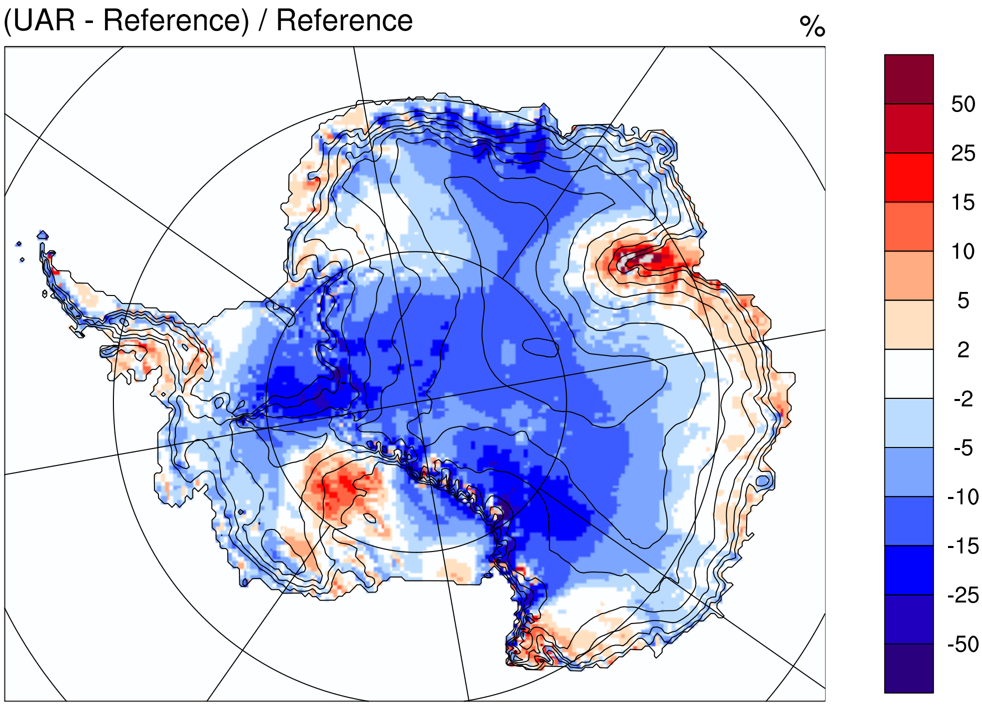
Table 1*: Statistics of modelled SMB for Thwaites Glacier catchment, West Antarctica. The mean 1980-2009 SMB derived by snow radar is 457 mm w.e. a^{-1}.*

Model Simulation	Correlation	RMSD mm w.e. a^{-1}	Bias mm w.e. a^{-1}
ERA-Interim	0.93	78	-75
Reference run	0.69	48	-17
UAR run	0.91	43	-35

And the Table is cited on P6 L16 and this paragraph is adjusted at P6 L22:
"RACMO2 is on average less than 2% drier than observed, leading to a lower RMSD. However, much of the representation…"
and P7 L7
"…as the ERA-Interim, and has the lowest RMSD."

RC P7, section 3.3: As well as being wider than in RACMO, the AP orography in ERA-Int is also lower, which will affect the magnitude of the orographic precipitation field as well as its spatial extent.
AC: This is indeed true. P7 L11-14 are, therefore, extended to
"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 and the maximum elevation of the mountain ridge is reduced. UAR thus introduces topographic effects at locations where they are not modelled by RACMO2 and less topographic effects at the mountain ridge."

RC Figure 3: Would it be better to display the change as a percentage, rather than an absolute difference?
AC: This figure is replaced as suggested. The Figure and caption now reads



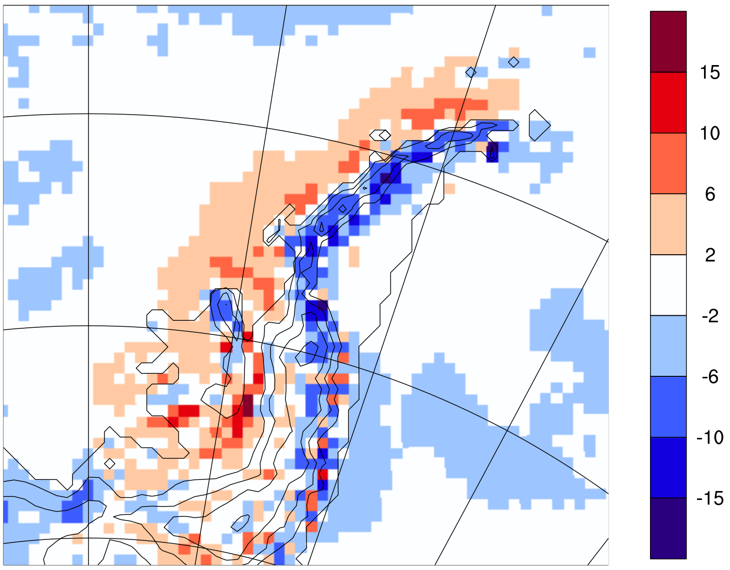
Difference in SMB (%) between the UAR and reference RACMO2 simulation for 1979-2013. Grid points with negative SMB in the reference simulation are masked grey.

RC Figure 4: Caption needs to make clear that the data are for the region shown in figure 2.

AC: The caption is adjusted to

"Observed and modelled integrated annual SMB for Thwaites Glacier catchment, West Antarctica (Fig. 2)."

Finally, while rechecking all data we found that there was a small calculation error while creating Fig. 5, which alters the overall mean value. The correct Figure is now



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Brief Communication: Upper air relaxation in RACMO2 significantly improves modelled interannual ~~SMB~~ surface mass balance variability in Antarctica

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Abstract. The regional climate model (RCM) RACMO2 has been a powerful tool for improving ~~SMB~~ surface mass balance (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~~ Antarctic 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 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~~ obtained 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~~Over Antarctica, where the variability is set by the large-scale circulation, a RCM ~~cannot~~ will unlikely improve upon the reanalysis interannual variability ~~because the variability is set by the large-scale circulation~~unless data assimilation is applied. RACMO2 in its default version neither has data assimilation nor relaxation to ~~boundary conditions~~ large-scale forcing fields 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~~ large-scale forcing fields (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~~ large-scale forcing fields 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~~forcing fields. 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~~large-scale forcing fields. 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.

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~~ large-scale forcing 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~~ (European Centre for Medium-Range Weather Forecasts Integrated Forecast Systems) and a multilayer 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.

This relaxation is implemented in the following manner and is only applied on temperature and wind fields. Humidity fields are not relaxed because that would lead to undesired distortions to the modeled clouds and precipitation fluxes, as already observed in the lateral boundary relaxation zones. 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

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

where $\Phi(\boldsymbol{x})_\mathrm{R}$ and $\Phi(\boldsymbol{x})_\mathrm{B}$ are the specific values from RACMO2 and the ~~boundary fields~~large-scale forcing, 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

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

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 $\mathrm{m\,a.s.l.}$ 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 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,~~ At the 500 ~~temperature (not shown) increases~~ hPa level, temperatures increase above Antarctica by 0.2 to 0.6 K ~~while the relative humidity decreases~~ (not shown) while relative humidities decrease by 0 to 2 %. All in all, the difference in the modeled mean climate between the reference and UAR runs is very limited. For example, mean surface pressures and 2 m temperatures differ only at max 0.7 hPa and 0.6 K, respectively.

3.2 Interannual variability

In Fig. 4 and Table 1, the integrated annual SMB derived from observations, ERA-Interim, and the two RACMO2 runs ~~is~~ are displayed. The ERA-Interim SMB, derived from precipitation minus sublimation, is systematically lower ~~the the~~ than 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~~ , leading to a lower RMSD. However, 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, and has the lowest RMSD.

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 and the maximum elevation of the mountain ridge is reduced. UAR thus introduces topographic effects at locations where they are not modelled by RACMO2 ~~. This artefact affects~~ and less topographic effects at the mountain ridge. These artefacts affect 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. A second test, in which only the stratosphere was constrained, i.e. relaxation for $\sigma \leq 0.25$ (Eq. 2), showed no improvement of the patterns over the AP while the correlation of modelled SMB with snowradar data for Thwaites glacier basin clearly deteriorated. 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 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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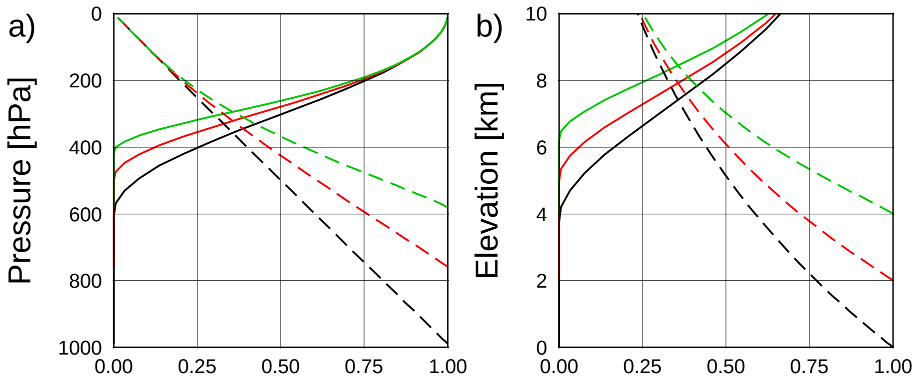

Fig. 1. $\lambda_\sigma(\sigma)$ (solid lines) and σ (dashed lines) as function of **(a)** pressure and **(b)** elevation for a location at 0 (black lines), 2000 (red lines) and 4000 (green lines) $\mathrm{m\,a.s.l.}$, respectively.

Table 1. Statistics of modelled SMB for Thwaites Glacier catchment, West Antarctica. The mean 1980-2009 SMB derived by snowradar is 457 mm w.e. a^{-1}.

Model simulation	Correlation (r) []	RMSD [mm w.e. a^{-1}]	Bias: [mm w.e. a^{-1}]
ERA-Interim	0.93	78	-75
Reference run	0.69	48	-17
UAR run	0.91	43	-35

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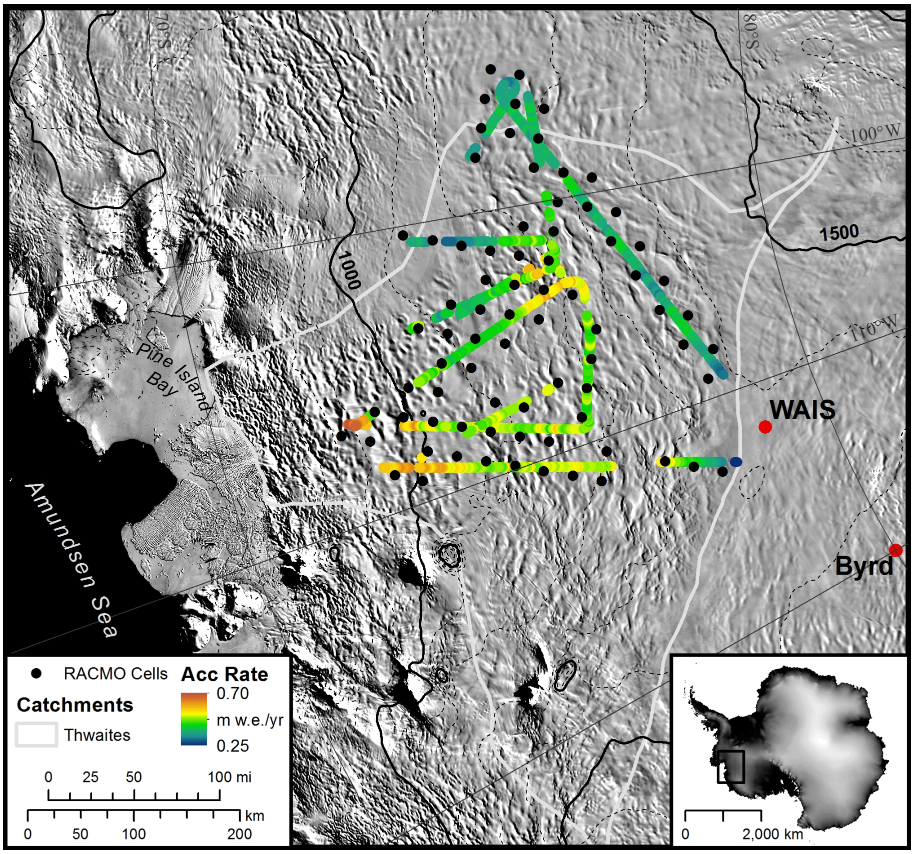

Fig. 2. Map of the study area, including catchment delineation (white line), elevation contours (black lines), radar-derived SMB and the location of the RACMO grid points used for comparison (black dots). The background image is de MODIS Mosaic of Antarctica (Scambos et al., 2007).

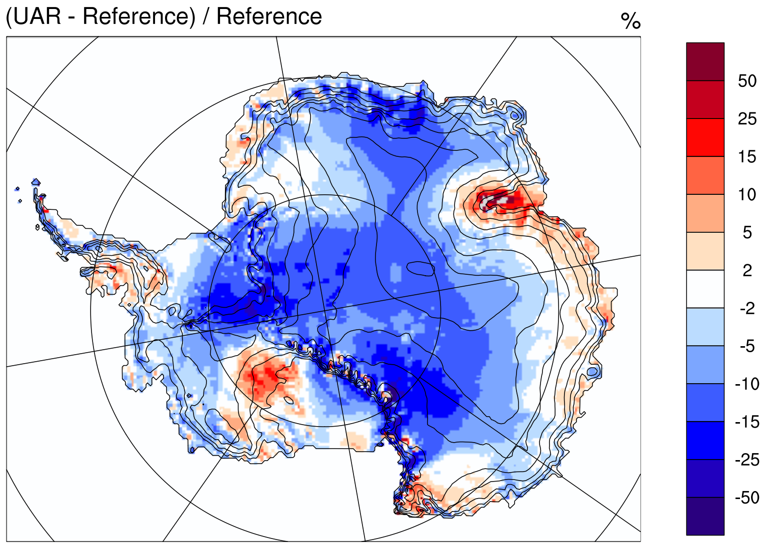

Fig. 3. Difference in SMB (%) between the UAR and reference RACMO2 simulation for 1979–2013. Grid points with negative SMB in the reference simulation are masked grey.

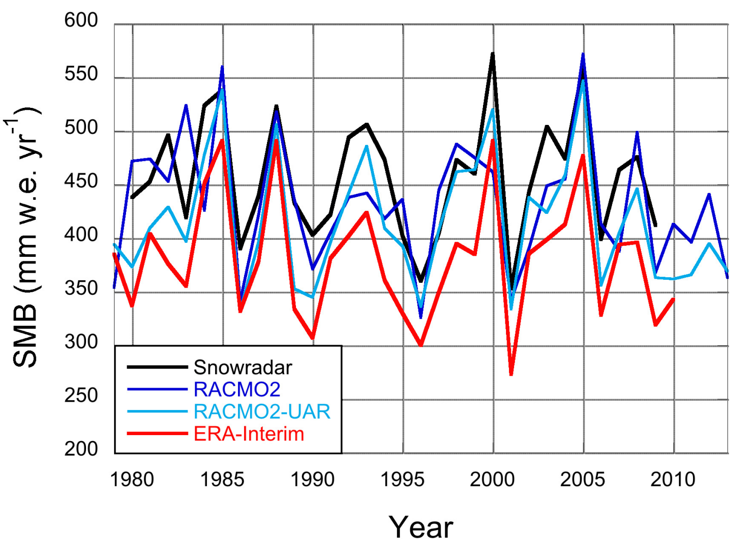

Fig. 4. Observed and modelled integrated annual SMB for Thwaites Glacier catchment, West Antarctica (Fig. 2).

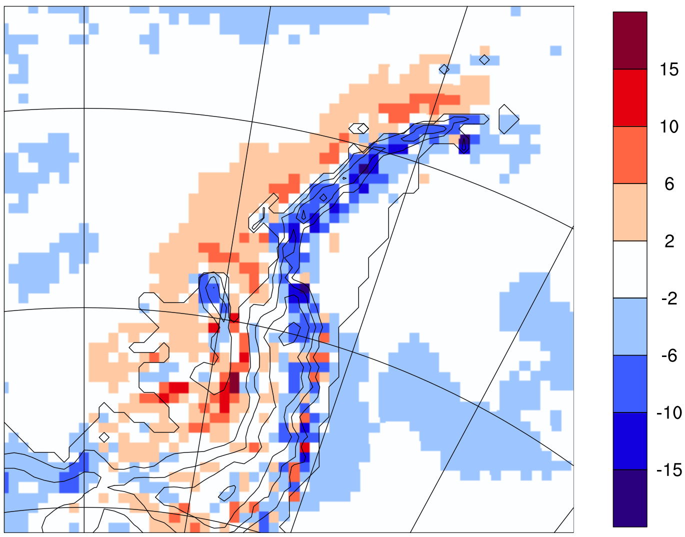

Fig. 5. Relative difference [%] in precipitation between the UAR simulation and the reference RACMO2 simulation over the Antarctic Peninsula.