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

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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.

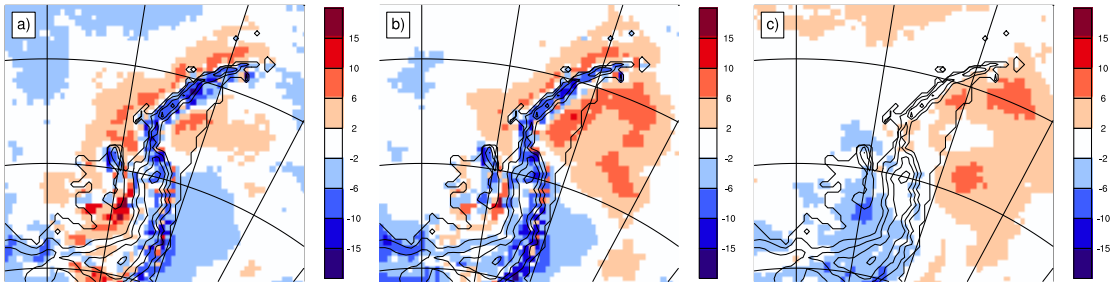


***Figure 1**: Relative change of precipitation for 1979-1993 for **a)** σ = 0.6, **b)** σ = 0.25. **c)** Difference between b) and a).*

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.

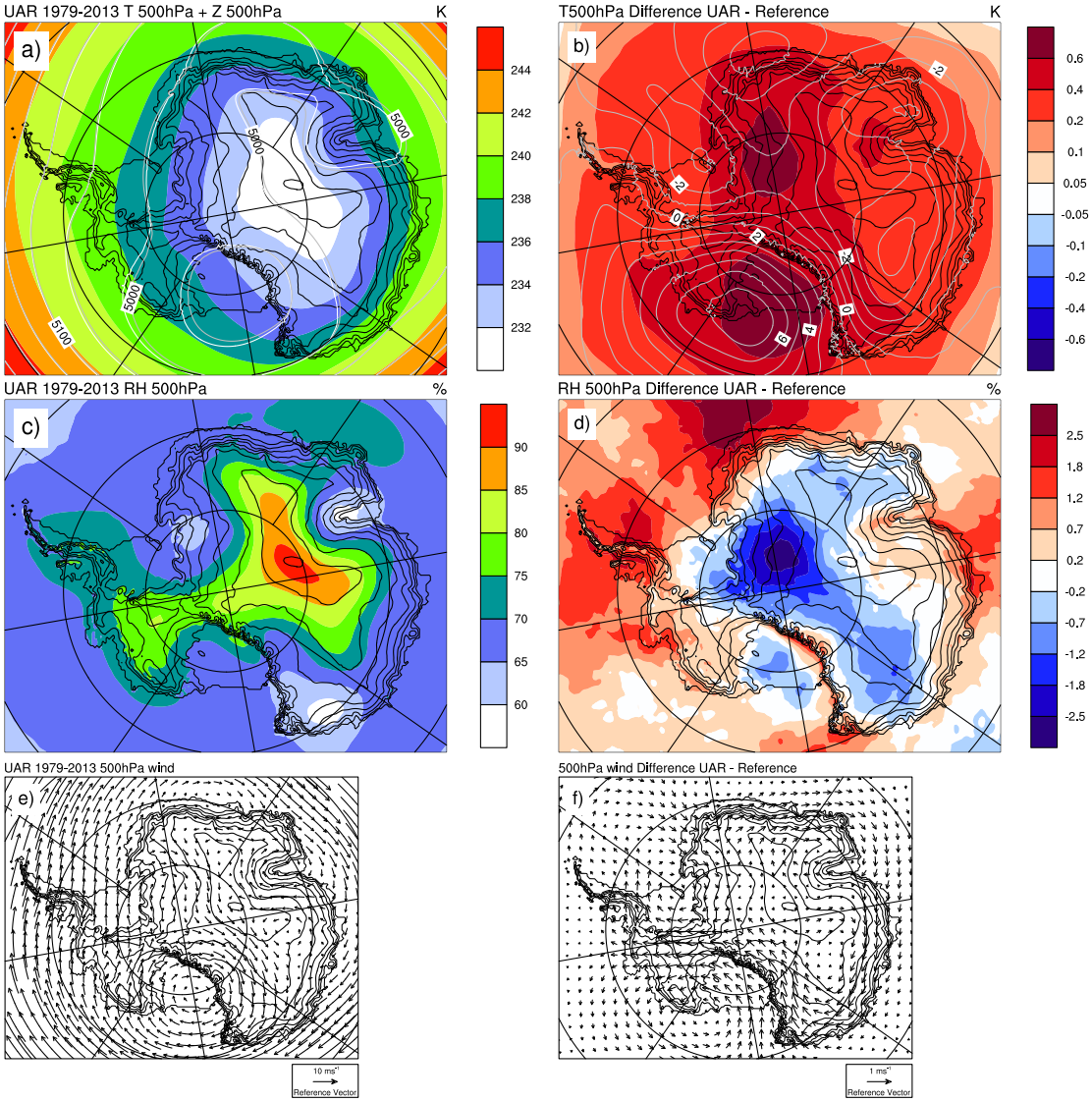


***Figure 2**: 1979-2013 500 hPa **a)** Temperature (colors) and elevation (grey lines), **c)** relative humidity and **e)** winds modeled by RACMO with using UAR. The difference between the UAR and reference simulation is given in figures **b)**, **d)** and **f)**. In figure a), Z 500hPa from the reference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

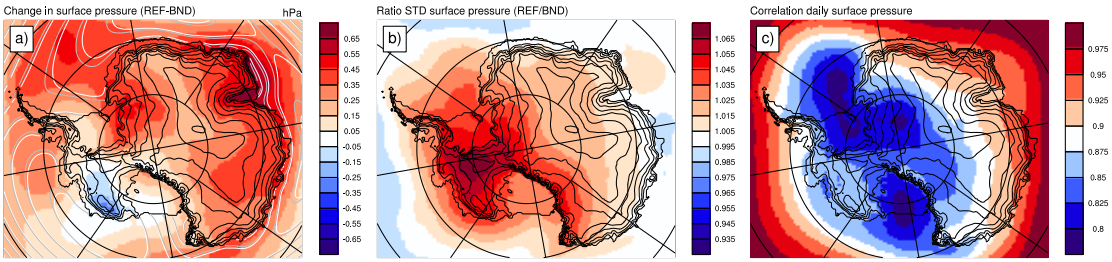


Figure 3: **a)** mean difference in surface pressure. Over sea, isobars are drawn every 2 hPa with the reference run and UAR run in white and grey, respectively. **b)** Ratio of the standard deviation of daily surface pressure. **c)** Correlation between daily surface pressures. All plots used data from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

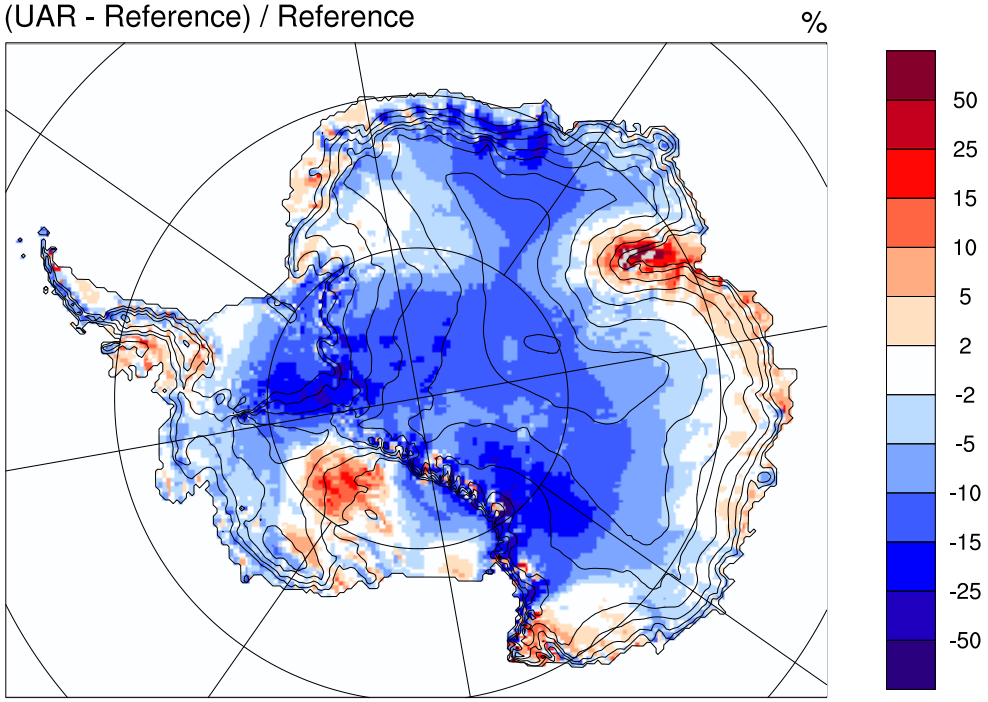
***Table 1**: Statistics of modelled SMB for Thwaites Glacier catchment, West Antarctica. The mean 1980-2009 SMB derived by snow radar is 457 mm w.e. a^{-1}.*

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