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Interactive comment on "A spectral nudging method for the ACCESS1.3 atmospheric model" *by* P. Uhe and M. Thatcher

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We thank the reviewer for taking the time to review our manuscript and for their valuable feedback. We have taken each comment into account and believe the revised manuscript will be much improved with these modifications. See below our response to each of the comments.

General comments:

This paper describes a new spectral nudging scheme that has been implemented in the ACCESS climate model in order to constrain the model toward ERA-Interim (ERAI) reanalysis. The spectral nudging approach applies a low-pass spectral filter so that only large spatial scales are constrained. This filtering approach offers flexibility compared

to Newtonian relaxation methods by allowing for the selection of the length scales as well as temporal scales to nudge. Since it is computationally expensive, the authors test implementations of 1-D filters compared to 2-D filters, as well as reducing the frequency that nudging is applied. Their analysis compares 500 hPa temperature between ERAI and several simulations including control (not nudged), Newtonian relaxation nudging, and 1-D and 2-D spectral nudging with several length scales. Based on their analysis, they conclude that using 1-D filters applied first in the meridional then zonal direction, and nudged once per hour, is the optimal, computationally efficient configuration. The topic of the paper is a good fit for the scope of the journal. The description of the methods and results are clear. And the experiment design, testing several length scales and soft vs. hard nudging, is appealing. However, the analysis is very limited and only evaluates the impact of nudging on one model field (500 hPa temperature). Major revisions, providing much more detailed evaluation of the impact of this nudging approach on the simulated results, would be a greater benefit to the scientific community. Observationally constraining a climate model, as is done here, implies a balance between (a) keeping the model state close to that of the host (ERAI) and (b) allowing the model to behave as it would in a "free-running" mode. The balance between (a) and (b) depends on the application. For example, Zhang et al. [2014] evaluate the use of nudging for aerosol-climate studies and find an undesirable impact of nudging on cloud and precipitation processes when strong temperature nudging is included, therefore suggesting only nudging horizontal winds for these types of studies. Jeuken et al. [1996] discusses in detail the implications for what variables are nudged and what relaxation times are used, identifying important considerations including: (1) how well the nudged fields (e.g. T, U, and V) match the reanalysis, (2) the magnitude of nudging tendencies (model forcing) compared to model physics tendencies, and (3) the impact of nudging on unconstrained model fields (e.g. humidity, cloud water content, precipitation, etc.). In this study only (1), how well the model is constrained, is evaluated, and only for 500 hPa temperature. For any application of this approach, it would be helpful to understand its impact on (2) model tendencies and (3) unconstrained model fields. The flexibility to nudge only large-scale features likely has benefits for reducing impacts on model behavior that can result from Newtonian relaxation methods, while still constraining circulation and meteorology. It is recommended that the analysis here be expanded beyond just evaluating 500 hPa temperature.

Response:

Although the original manuscript was focused on verifying that the scale-selective filter worked as designed, we acknowledge the reviewer's advice that the manuscript requires more evaluation so that the reader can better understand the implications of the technique. We have already expanded our analyses to include T,U and V on 850, 500 and 250 hPa levels, which depicts how surface errors (i.e., over land) become more pronounced as we approach the surface due to differences between ERA-I and ACCESS's land-surface parameterisation and topography. We have also analysed unconstrained variables for precipitation and mean sea level pressure on the advice of the reviewer, as these fields are well constrained by observations. As suggested by the reviewer, we indeed find that the scale-selective filter has advantages with rainfall, compared to the Newtonian relaxation. Unfortunately, the particular version of ACCESS used for the experiments did not support output for model tendencies, although we have investigated the behaviour at diagnostic grid points. However, we feel that the comparison with the control (non-nudged) experiment provides similar information in-so-far as to where ERA-Interim and ACCESS disagree and therefore where the model tendencies would be the greatest (i.e., as for air temperature). Nevertheless, we would attempt to clarify this issue in the revised manuscript. We appreciate the reviewers comments on the design of the scale-selective filter and what fields to nudge. The Kanamaru and Kanamitsu reference that we mentioned also raises similar issues. In the end we elected to stay consistent with the Telford approach and constrain T,U and V, which is a popular choice with many models. We also find nudging the temperature is quite useful for our atmospheric chemistry experiments, although this was not discussed in our manuscript in an attempt to keep the paper more focused on the issue of nudging.

Nevertheless, we intend to elaborate on the design choices in the revised manuscript and thank the reviewer for the additional references.

Specific comments:

1. Page 6686 - line 17: A more detailed description of how ERAI was interpolated and prepared for the ACCESS grid would helpful. Vertical interpolation can create artifacts due to differences in model/reanalysis topography that can impact lower pressure levels high above the surface. Its possible the high temperature RMSE over mountain regions shown in Figure 1 is the result of topographic differences that were not properly accounted for in the interpolation scheme. How were ERAI and ACCESS topographic differences accounted for? What type of horizontal and vertical interpolation was used for temperature and winds? More description of the ERAI regridding procedure is needed.

The reviewer raises a valid point regarding the vertical interpolation method. For comparison with the original UM nudging paper by Telford et al, we elected to retain the same vertical interpolation that is based on a piece-wise linear interpolation based on the log of the pressure. No special treatment for orography was included for consistency with Telford et. al. Nevertheless, the issue certainly warrants more discussion in the revised manuscript and we can comment on other methods such as exploiting the lapse rate to correct air temperature, such as that used by the Thatcher and McGregor reference. We will also include that ERAI data was interpolated to the ACESS horizontal grid using a bicubic interpolation method.

2. Page 6687 - line 25: Figure 2 shows the "difference in variance of air temperature", but it is not discussed why this is a useful metric to evaluate or why the annual variance is too large in the control simulation and generally too small in the nudged simulations. A potentially more useful metric to quantify the degree to which ACCESS is constrained to ERAI would instead be the "variance of the difference in air temperature", which would show how nudging constrains the model to vary in the same way as ERAI, rather

than just the amount of annual variability. Otherwise, more discussion is needed to clarify and explain the results shown in Figure 2.

Our aim in the original manuscript was to highlight the impact of nudging on the variance of fields as well as the mean behavior. We have analysed the variance of the difference, but we found that the errors were similar in spatial patterns and magnitude as was shown for the RMSE plots in figure 2. For this reason we felt that the difference in variance plots showed that the non-nudged ACCESS model underestimated this behavior and was somewhat corrected by the nudging. Again, we will clarify this explanation in the revised manuscript and we acknowledge the reviewers concern that the reasons for this analysis are unclear in the current manuscript.

3. Page 6689 - line 1: It could be useful to show the map of RMSE with 2D and 1D filters (as in Figure 1) to justify that not only global mean error is similar, but the spatial distribution as well.

For the purposes of the manuscript we thought that showing zonal averaged RMS differences in figure 3 was the clearest way to represent the differences in spatial distribution of the 1D filters as the output from the two versions of the 1D filter and the 2D filter can be quite similar when viewed as a map. After consideration of the reviewer's comment, we have decided that it is helpful to modify figure 3 to show the zonally averaged RMSE relative to ERAI rather than relative to the 2D filter, and also include the RMSE of the 2D filter in this plot. This shows how similar the three methods are, apart from in the high latitudes. Again, we will endeavor to clarify the reason for using figure 3 in the revised manuscript.

4. Page 6689 - line 9: Figure 4 shows RMSE levels off after 4 days. Were these first few days included in the subsequent analysis (all other figures) or was there some spin up time before the analysis period? Spin up is usually needed, and these differences between the initial conditions and reanalysis should not be part of the nudging evaluation.

Although we attempted to keep the experimental design simple for the reader, we acknowledge that the spin-up issue may be of some concern. To address this point, we have regenerated the plots and recalculated other values after omitting the first 10 simulation days, which avoids any spin-up problem. The results are very similar to those shown in the original manuscript and do not affect any of the conclusions of the manuscript. Nevertheless, this is a straightforward amendment to the manuscript that we are happy to undertake.

5. Page 6690 - line 7: A figure simply showing the difference between ACCESS simulations and ERAI could be helpful for illustrating that spectral nudging errors are random (positive and negative) and Newtonian relaxation is systemically warmer. What is the reason for this difference in the structure of errors with different approaches? Is this a result that is expected with the different implementations of nudging?

We believe that the differences between the air temperature errors in the different nudging approaches arises from their ability to compensate for the temperature bias in the control simulation relative to ERA-I. This was not a result that we expected from the different implementations of nudging, especially as we tailored the experiment design to make the comparison between the Newtonian relaxation and scale-selective filter as consistent as possible. The reasons for this difference are not entirely clear, although we suspect a form of 'steady-state' error arising in the Newtonian relaxation that is well known for proportional-only control methods. The data in table 1 suggests that hard spectral nudging with larger λ seems to help reduce the systematic error, implying that corrections of only larger scale errors can slow the growth of the ACCESS temperature error. However, this could be a somewhat model dependent result and we do not wish to overgeneralize the results at this stage. Although we can provide plots of the difference between the ACCESS simulations and ERA-I, the bias is easier to identify in the GAE and we felt that the table reflected this result without including an additional plot. We plan to expand on our discussion of this issue of the revised manuscript to reflect the above points.

6. Page 6690: It would be helpful to add the control results to Table 1 and include RMSE and GAE for U and V as well.

We are very happy to include the control results in Table 1 as suggested by the reviewer. We are also happy to add the RMSE and GAE for U and V.

7. Do RMSE and RMS (Figures 1 and 3) show a similar result for horizontal winds? What do the errors look like for other pressure levels higher and lower in the atmosphere?

As discussed in the general comments, we are happy to address the reviewers comments with the inclusion of T, U and V errors for 850, 500 and 250 hPa levels. We have already extracted this data from the simulations and composed the relevant plots. The plots show an increasing difference in behavior between ACCESS and ERA-I as we approach the surface, likely to be arising from differences in the representation of land-surface processes and the topography, as well as because the bottommost levels are not nudged. We intend to include a discussion of these issues in the revised manuscript.

8. What is the magnitude of the nudging tendencies compared to model physics and dynamics tendencies? How much influence do model physics have on the simulation when nudging is applied?

As mentioned in the general comments, we acknowledge the reviewers interest in showing the model tendencies. Although this information was not available in the output of ACCESS in the version of the model we used, we instead tried to convey similar information from the comparison with the control experiment. For example, it is clear that there is a noticeable temperature bias in the control run that the nudging tendencies will need to correct. Since this temperature error is successfully corrected by the nudging, then the nudging tendencies need to be significant compared to the tendencies arising from the rest of the simulation. It was our intention to try to keep the analysis based on fields that are reasonable well constrained by observations and

use the control experiment to explain where the nudging is making significant changes to the non-nudged model evolution. In any event, we would make these issues much clearer in the revised manuscript, including commenting on the relative size of the correction with respect to the control experiment.

9. How does the implementation of nudging impact convection, clouds, precipitation, surface fluxes, TOA radiation, etc.?

We thank the reviewer for their advice on analyzing the unconstrained fields. This is an effective test of how the non-nudged components of the model respond to the nudged fields. We prefer to concentrate our analysis on fields that are well constrained by observations and that are relatively easy to compare between models. So to that end we have concentrated our additional analysis on precipitation and mean-sea-level-pressure, which somewhat reflect the implications for convection, etc. The results for precipitation suggest that the scale-selective filter may have an advantage over the Newtonian relaxation in that case. We intend to add an additional section to the revised manuscript discussing the implications for the unconstrained precipitation and mean-sea-level pressure fields.

10. Page 6690 - line 5: Should it be λ = 0.2 instead of 0.1?

It was our intention to use λ =0.1, although we can understand why λ =0.2 seems to show a similar point. Our concern was the size of the error in the GAE estimate may obscure the differences arising from the different nudging techniques. Therefore we elected to use an example where the estimated error in GAE did not obstruct the result. Again, we are happy to clarify this issue in the revised manuscript.

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