Dear Dr. Cheng,

On behalf of the co-authors, I submit a revised version of the manuscript titled “On the use of nudging for aerosol-climate model intercomparison studies” for your consideration of publication in ACP.

We have responded to all referees’ comments and revised the manuscript accordingly. The point-to-point reply to the referees has been uploaded to the interactive discussion webpage and is attached below.

In addition, we added a new section (Sect. 5, Discussions) where results from a second aerosol-climate model ECHAM6-HAM2 are briefly discussed to demonstrate that the revised nudging strategy we recommend for CAM5 can also benefit other models. Please also note that we’ve added Drs. David Neubauer and Ulrike Lohmann (ETH) to the author list in recognition of their essential contribution in providing the ECHAM results.

Changes to the original manuscript are highlighted with blue fonts.

We hope you find the revision satisfactory and look forward to your favorable decision.

Sincerely,

Kai Zhang

Reply to Anonymous Referee #1

Correspondence to:
Kai Zhang (kai.zhang@pnnl.gov)
Pacific Northwest National Laboratory

We thank referee #1 the helpful and constructive comments. Below please find our response to the review comments.

This technical note on the use of nudging in studies of aerosol impacts on clouds and climate in global climate modeling provides an important methodological refinement with a wide range of applications. The manuscript presents the issues and results clearly. A few minor additions could help provide better context for a broad range of studies:

Comment: *1. The authors apply nudging as the only data assimilation technique, and would benefit from reflecting on the applicability of the findings to other assimilation techniques widely employed in climate and aerosol modeling. Are any of the qualitative findings inherently specific to nudging, or would they be expected to perform similarly for variational assimilation approaches?*

Reply: Our understanding is that most other data assimilation techniques are used in climate and aerosol modeling for the purpose of initializing forecasts/predictions, producing reanalysis, constraining regional downscaling, estimating parameters, etc. In such cases, the goal is to keep the model state as close as possible to the ``truth". In the model intercomparison we discussed in the paper, however, the intention is to expose model biases and inter-model discrepancies, and use nudging to exert a continuous constraint to suppress the impact of natural variability. We think these are two different types of applications with different needs. We've added a clarification on this in the revised manuscript (please also see our reply to comment 2 below).

Comment: *2. Would a similar strategy apply to the investigation of aerosol indirect effects through ice clouds at regional and local scales?*

Reply: We think the answer to this question would depend on the purpose and needs of the investigation.

If, like in the AeroCom intercomparison, the purpose is to characterize model responses, then a similar strategy can be applied, although there is a caveat that in smaller-scale transient simulations where the dynamical responses are an important component of the aerosol indirect effect, nudging winds may suppress the feedback and change the magnitude of the signal.

If the purpose of using nudging (or other assimilation techniques) is to reduce model biases, then the wind-only nudging might not provide a sufficiently realistic simulation.

A discussion is added to the revised manuscript at the end of the "Conclusions" section:

"As an additional remark we note that nudging, and in a broader sense data assimilation, has been widely used in weather and climate related research and applications. Examples include initialization of weather forecast and climate prediction, boundary control and large-scale steering for downscaling using regional models, and parameter estimation (including reanalysis). The optimal assimilation strategy for an application must be determined according to the specific needs. For example for prediction and downscaling problems where the purpose of data assimilation is to keep the model state as close to the ``truth" as possible (or in other words, to reduce model errors), constraining only the horizontal winds as discussed here may not be sufficient, especially if the model tends to generate large temperature biases. On the other hand, if the goal is to suppress the influence of natural variability and meanwhile let the model express its own characteristics (i.e., to expose model biases or inter-model discrepancies), like in the case of the AeroCom ice-AIE intercomparison, then our method can be a good option, and may potentially be used for regional modeling as well. In certain applications and regimes where wind differences between the driving data and the simulated values have significant impact on important features of the model results, or when the dynamical responses play an important role, one may need to loosen the constraint on winds as well, for example in certain geographical regions or in the near-surface levels. Again, the optimal experimental design depends on the specific needs of the conceived application."

Reply to Anonymous Referee #2

Correspondence to:
Kai Zhang (kai.zhang@pnnl.gov)
Pacific Northwest National Laboratory

We thank referee #2 the helpful and constructive comments. Below please find our response to the review comments.

This manuscript explores different nudging experiments using the Community Atmosphere Model. The manuscript is of significance to the modeling community given the decision to use these results as model guidance for the AeroCom aerosol-climate model intercomparison initiative. The general guidance is to nudge the wind field and not temperature as nudging towards temperature creates issues when trying to estimate aerosol impact on radiation and clouds. The manuscript also provides more general guidance to the modeling community. The manuscript is well written with very well designed experiments to investigate the impact of nudging while retaining estimates of the aerosol impact on the climate. A few minor changes and additions are recommended below.

Comment: *1. The argument that nudging to temperature is a valid argument, but some additional explanations would be helpful. In particular, some of the largest temperature corrections for nudging (mid to high latitudes) do not coincide with the max. mean frequency of occurrence for homogeneous ice nucleation (tropics).*

Reply: The largest temperature biases in Fig. 3 appear in the polar stratosphere, a feature commonly seen in many climate models. Homogeneous ice nucleation rarely happens in these regions in CAM5 because (1) the air is relatively dry, and (2) homogenous nucleation is also inhibited by heterogeneous nucleation, which requires lower relative humidity.

In the revised manuscript we added a masking in Figs. 3 and 7 and only show temperature biases/corrections in regions where the mean ice crystal number concentration exceeds 5 crystals per gram air in the free-running CAM5. There reasoning is, since we want to understand the discrepancy in longwave cloud forcing (LWCF) between the nudged and unconstrained simulations, and the LWCF is mainly associated with ice clouds, we focus on the regions where there is appreciable amount of ice clouds in the CLIM simulation and try to understand what is the impact of nudging there. Regions where ice clouds rarely occur are not very relevant for our investigation.

Comment: *2. Figure 4 needs to be clarified. How is the frequency of occurrence being calculated? Is the frequency from daily model output? Would be helpful to have the color bar as a percent.*

Reply: The caption has been revised. Unit is changed to percent, and we clarify that the frequency of occurrence is calculated using an online nucleation counter, which keeps track whether there is homogeneous ice nucleation happening at each model time step.

Comment: *3. Figure 5 also shows largest sensitivity in the tropics but Figure 6 tries to justify using global average precipitation. It would be helpful to have a separate analysis on the tropics compared to the mid-to-high latitudes.*

Reply: We analyzed the convective precipitation in the tropics and mid-to-high latitudes separately, and found that their responses to nudging are very similar. In the revised manuscript we show the tropical precipitation in Fig. 5b.

Comment: *4. Figure 7: Clarify caption from "5 yr mean zonal mean temperature".*

Reply: It now reads:

"Left column: 5 yr (2006–2010) mean zonally averaged temperature differences between nudged and free-running CAM5 simulations. Right column: same as left column but between nudged CAM5 simulations and the ERA-Interim reanalysis. Simulations shown in the upper and lower rows used the anomaly nudging described in Sect. 2.2 (NDG ERA UVTa) and the wind-only nudging (NDG ERA UV), respectively. Like in Fig. 3, regions with mean ice crystal number concentration lower than 5 g^{-1} are masked out in gray."

Comment: *5.* Figure 8: Caption should include (U, V, T, Q, Z3).

Reply: Corrected.

Comment: *6.* There are a lot of studies working on regional application of aerosol impacts using limited area models. Should mention this application as it could be a great lead for future studies wanting to understand the impact of nudging of aerosols for regional applications.

Reply: In response to this suggestion and the other referee's comments, we added a paragraph of discussion at the end of the paper:

“As an additional remark we note that nudging, and in a broader sense data assimilation, has been widely used in weather and climate related research and applications. Examples include initialization of weather forecast and climate prediction, boundary control and large-scale steering for downscaling using regional models, and parameter estimation (including reanalysis). The optimal assimilation strategy for an application must be determined according to the specific needs. For example for prediction and downscaling problems where the purpose of data assimilation is to keep the model state as close to the ``truth" as possible (or in other words, to reduce model errors), constraining only the horizontal winds as discussed here may not be sufficient, especially if the model tends to generate large temperature biases. On the other hand, if the goal is to suppress the influence of natural variability and meanwhile let the model express its own characteristics (i.e., to expose model biases or inter-model discrepancies), like in the case of the AeroCom ice-AIE intercomparison, then our method can be a good option, and may potentially be used for regional modeling as well. In certain applications and regimes where wind differences between the driving data and the simulated values have significant impact on important features of the model results, or when the dynamical responses play an important role, one may need to loosen the constraint on winds as well, for example in certain geographical regions or in the near-surface levels. Again, the optimal experimental design depends on the specific needs of the conceived application.“