Point-by-point Reply to Comments from Reviewer 2

We greatly appreciate the comments from Dr. William Collins. Below please find our reply (dark red).

This was a clear study that successfully explained some biases in the previous nudging schemes. The comments on time resolution will be useful to the community which generally used 6-hourly data.

For the aerosol forcing why is 6-hour nudging used when the authors have shown that 3-hour is preferred? This experiment should be repeated with the 3-hour resolution.

We have performed the nudged simulations with the 3-hour constraining data and evaluated the impact on the effective aerosol forcing (F_{aer}) estimate. As shown in the following figure, the global annual mean F_{aer} estimated by the nudged simulations is not sensitive to the choice of the constraining data frequency.

For both UV-nudging (Figure 1a-b) and UVT-nudging (Figure 1c-d), the Faer estimates are similar for simulations with 6h constraining data (orange) and for those with 3-hour constraining data (blue). This applies to both the simulations nudged towards the model's own meteorology (solid) and simulations nudged towards ERA5 (hatched). The impact of constraining data frequency on present-day simulations is relatively small except in regions where strong diurnal variations exist (Section 3.2). Therefore, the impact on global and tropical mean estimates is small. If the investigation is for regions with strong diurnal cycles, using the 3h constraining data should be a better solution. We have added these discussions in Section 5 in the revised manuscript.

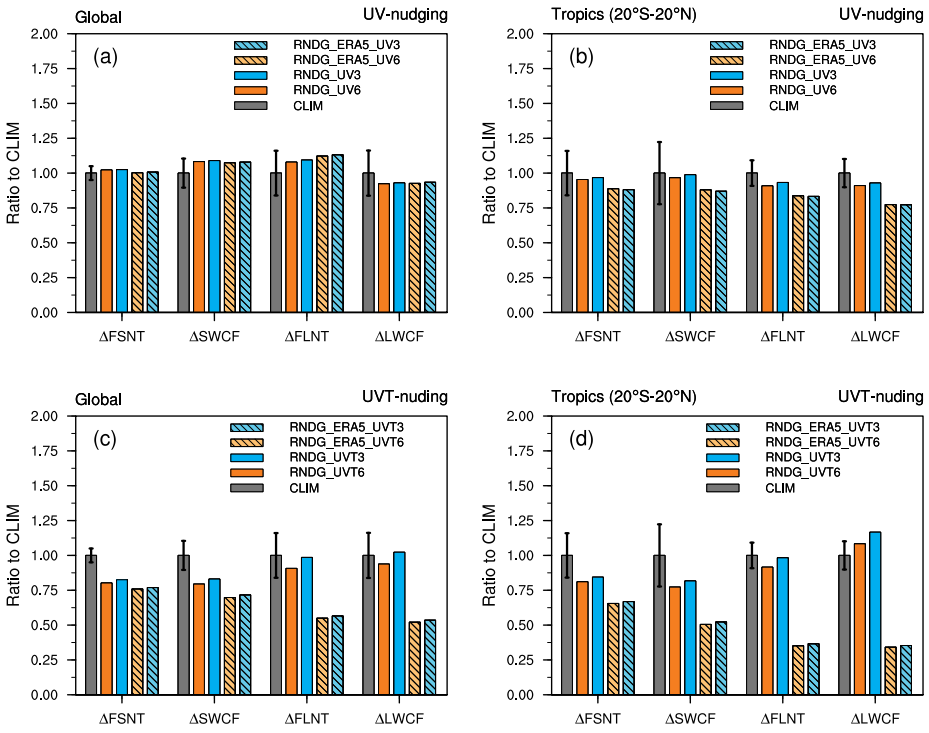

Figure 1. Global (a, c) and topical (b, d) mean annually averaged anthropogenic aerosol radiation effect (PD-PI differences, denoted by Δ) estimated by free-running (i.e., CLIM, grey bars) and nudged EAM simulations (colored bars). Shown in each panel is the ratio of the values from each simulation to corresponding values in CLIM. The original data can be found in Table S3. The vertical thin line and whiskers on the dark grey bar indicate the standard deviation of the 5-ensembles in CLIM. FSNT/FLNT is the TOA net shortwave/longwave radiation flux and SWCF/LWCF the shortwave/longwave cloud radiative effects. The top row compares the UV-nudging simulations with CLIM, while the bottom row compares the UVT-nudging simulations with CLIM. The solid color bars are for the nudged to CLIM simulations, while the hatched color bars are for the nudged to ERA5 simulations. The simulations are described in Section 2.3 and Table 1.

The authors could explain the issues with the temperature nudging more fully. The effects are attributed to biases. While this could be true for ERA, this should be much less significant for CLIM (fig 2(e)) and would be even less so for 3-hourly (in fig 4(d)). Is this actually removing a meteorological adjustment to the aerosols?

This is a good question. Our original statement is for the simulations nudged towards reanalysis. We have made additional analyses to further explain this and the effect in simulations nudged towards CLIM.

For the simulations (PD and PI) nudged towards CLIM (PD), we think the significant impact of temperature nudging is indeed due to the more constrained meteorological adjustment to the aerosol perturbation. The anthropogenic aerosols do have a small but significant impact on temperature, even when horizontal winds are nudged (c.f. Figure 2a–c). When the temperature is nudged, the associated responses in cloud processes could be changed (c.f. Figure 2d–f for cloud liquid water mixing ratio and Figure 2g–i for cloud ice water mixing ratio).

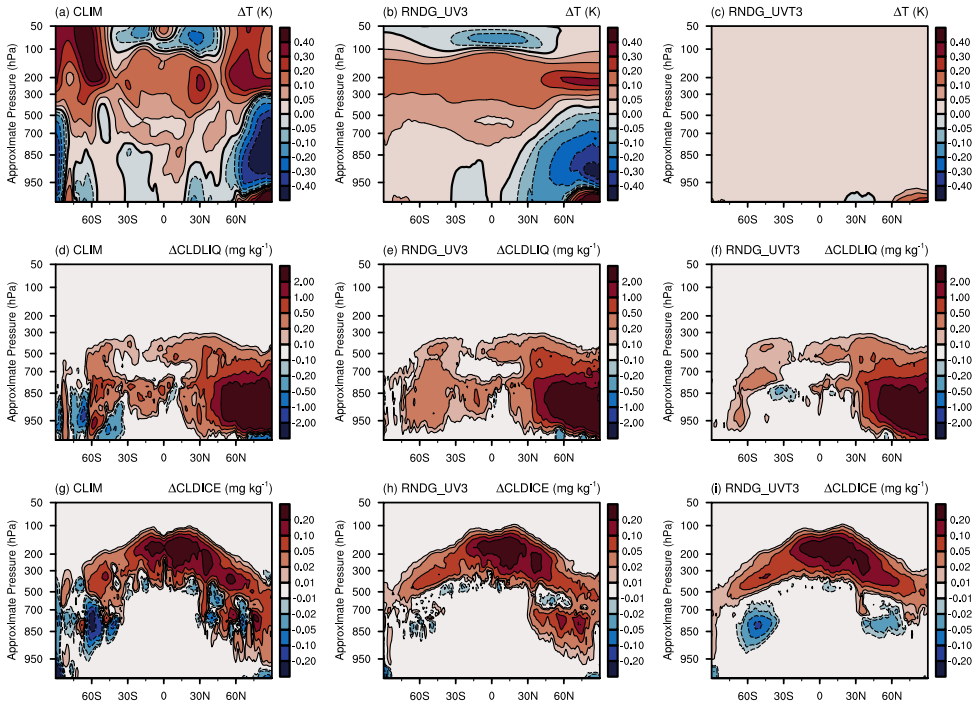

Figure 2. PD-PI differences in temperature (ΔT, unit: K, top row), cloud liquid water mixing ratio (ΔCLDLIQ, unit: mg kg^{-1}, middle row) and cloud ice water mixing ratio (ΔCLDICE, unit: mg kg^{-1}, bottom row) from the free-running (i.e. CLIM) and nudged EAM simulations. RNDG_UV3 (second column) is for UV-nudging, and RNDG_UVT3 (third column) is for UVT-nudging. The 3-hourly constraining data frequency is used for all nudged simulations. Both PD and PI simulations are nudged to CLIM (PD meteorology) in EAMv1. See details in Section 2.3 and Table 1.

For the simulations nudged towards ERA5, temperature nudging has a substantial impact on the ice cloud formation and the associated aerosol-induced radiative effects. The free-running EAMv1 has a 1–2 K cold temperature bias in the upper-troposphere (around 200 hPa) over tropical and mid-latitude regions (Fig. 3a), where small ice crystals are formed through homogeneous ice nucleation (Fig.4a). These small ice crystals have a large impact on the simulated cloud radiative forcing. When the cold biases are removed by reanalysis temperature nudging (Fig. 3b), there is a strong reduction in the simulated in-cloud ice number concentration (ICINC, Fig. 4b). Compared to CLIM (PD-PI), the ICNIC increase due to the aerosol perturbation is also much weaker in the reanalysis UVT-nudged simulations (Fig. 3d) and this will have a significant impact on the simulated changes in longwave radiative fluxes and cloud radiative forcing (ΔFLNT and ΔLWCF, hatched blue and orange bars in Fig. 1c-d). Our results are consistent with those of Zhang et al. (2014) who showed that the temperature nudging with corrections on the cold temperature biases in CAM5 also leads to a substantial decrease in the ice cloud amount and a weaker impact of anthropogenic aerosols on longwave radiation.

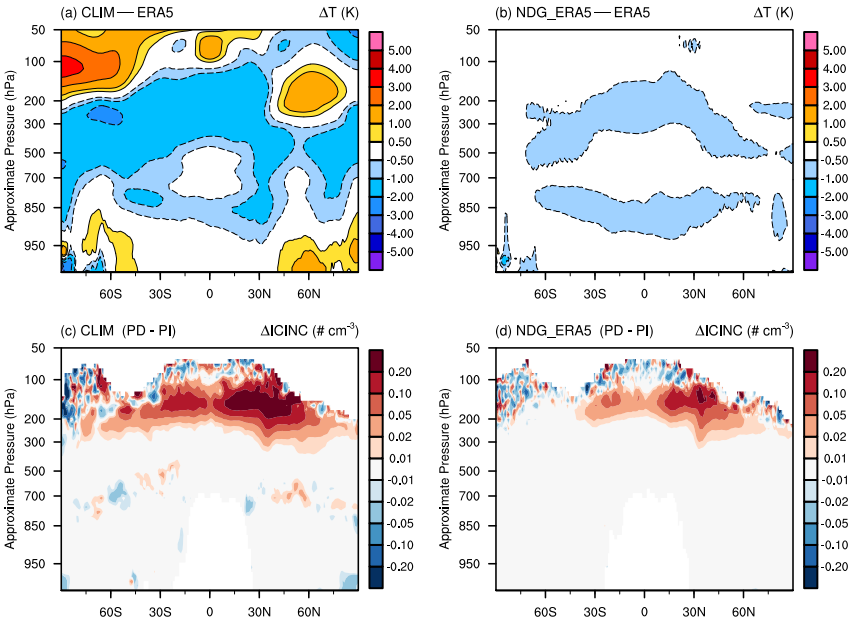

Figure 3. Top row: annual mean zonally averaged differences in temperature (ΔT, unit: K) between (a) CLIM and (b) nudged EAMv1 simulation and ERA5 reanalysis. The NDG_ERA5 in the figure caption is the acronym of RNDG_ERA5_UVT3 with nudging towards 3-hourly wind and temperature fields from ERA5 reanalysis. Bottom row: PD-PI differences of in-cloud ice number concentration (ΔICINC, unit: # cm^{-3}) derived from (c) free-running (i.e. CLIM) and (d) nudged EAM simulations (i.e. RNDG_ERA5_UVT3). See details in Section 2.3 and Table 1.

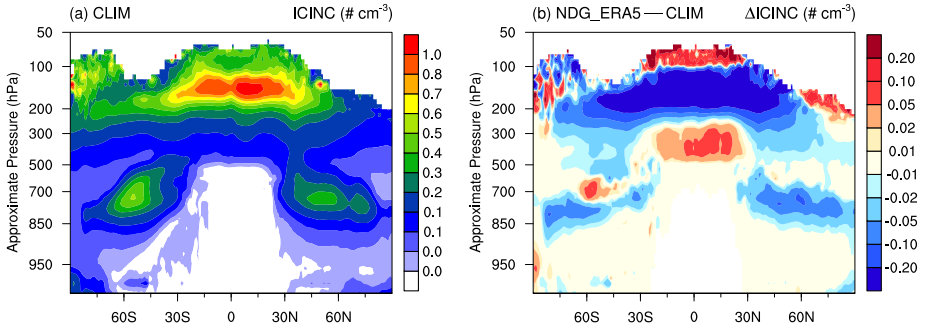

Figure 4. Annual mean zonally averaged (a) in-cloud ice number concentration (ICINC, unit: # cm^{-3}) from EAMv1 free-running simulation (i.e., CLIM), and (b) difference in ICINC (ΔICINC, unit: # cm^{-3}) between CLIM and nudged EAMv1 simulation. The NDG_ERA5 in the figure caption is the acronym of RNDG_ERA5_UVT3 (nudged towards 3-hourly wind and temperature fields from ERA5 reanalysis). All simulations used present-day (PD) aerosol emissions. See details in Section 2.3 and Table 1.

Specific points:

Figure 1: Why is the nudging tendency applied at a different place in the sequence to where it is calculated?

The original nudging implementation in E3SMv1 was taken from CAM5.4, which calculates the nudging tendency after dynamics, but applies the nudging tendency before dynamics.

In terms of time integration, this implementation treats the nudging tendency and physics tendency in parallel (i.e., parallel splitting). The total tendency (nudging + physics) will be diagnosed and applied as a forcing term in the physics-dynamics coupling calculation (Zhang et al., 2018). In this way, the model dynamics can adjust the wind and temperature fields to achieve geostrophic and thermal balances. On the other hand, we are not clear about all the previous testing during the nudging implementation development for CAM5.4, but very likely different implementations have been tested and evaluated, since Sun et al. (2019) and this study both shows good hindcast skill of the nudged E3SMv1 simulations.

We note that the nudging implementation can be very different in other models. For example, the other nudging implementation in the CAM5 model employed in Kopperman et. al. (2012) and Zhang et. al. (2014) chose to apply nudging tendency after the moist processes and radiative transfer, and before the coupling between the atmosphere, land, and ocean models (see Figure 1 in Zhang et. al. (2014)). In the same paper, Zhang et. al. also pointed out that the nudging in the ECHAM6-HAM2 model (Stier et. al., 2005, Zhang et al., 2012) chose to apply nudging tendency after model dynamics.

We have added further discussions in Section 2.2 in the revised manuscript.

References:

Kooperman, G. J., Pritchard, M. S., Ghan, S. J., Wang, M., Somerville, R. C. J., and Russell, L. M. (2012), Constraining the influence of natural variability to improve estimates of global aerosol indirect effects in a nudged version of the Community Atmosphere Model 5, J. Geophys. Res., 117, D23204, doi:10.1029/2012JD018588.

Stier, P., Feichter, J., Kinne, S., Kloster, S., Vignati, E., Wilson, J., Ganzeveld, L., Tegen, I., Werner, M., Balkanski, Y., Schulz, M., Boucher, O., Minikin, A., and Petzold, A.: The aerosol-climate model ECHAM5-HAM, Atmos. Chem. Phys., 5, 1125–1156, https://doi.org/10.5194/acp-5-1125-2005, 2005.

Zhang, K., Wan, H., Liu, X., Ghan, S. J., Kooperman, G. J., Ma, P.-L., Rasch, P. J., Neubauer, D., and Lohmann, U.: Technical Note: On the use of nudging for aerosol–climate model intercomparison studies, Atmos. Chem. Phys., 14, 8631–8645, https://doi.org/10.5194/acp-14-8631-2014, 2014.

Line 154: Please define how CF is calculated.

CF is defined as the sum of short-wave and long-wave radiative forcings. This definition has been added in Section 3 (Line 155) in the revised manuscript.

Figure 3: This is a useful figure that nicely explains the effects.

Thanks for your comment.

Line 345: The differences in emissions between 1850 and present should be detailed here or in the supplement.

Thanks for the suggestion. We have revised the description of aerosol emissions in Section 2.3 of the revised manuscript:

"Emissions of aerosols and their precursor gases of the year 2010 are used to represent the present-day (PD) condition. Emissions of the rear 1850 are considered as the pre-industrial (PI) condition. The major differences between PI (1850) and PD (2010) aerosol emissions include anthropogenic sulfur, black carbon, organic carbon, primary organic carbon, and SOA precursors (applied as yields) emissions. Biomass burning emissions are also slightly changed. Dust, sea salt, and marine organic aerosol emissions are calculated online based on surface wind speeds and other surface properties."

Line 364: It is not obvious why there should be biases when nudging to CLIM. However, if EAMv1 has notable biases then it is not clear why improving the temperatures by nudging to ERA5 doesn't give a more physical measure of the aerosol forcing than using the biased temperatures.

Since this comment is directly related to the major comment, please find our reply in the response to the major comments above.