Point-by-point response to the reviews

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We greatly appreciate the careful reviews and helpful comments from the anonymous reviewer and Dr. William Collins. Based on their comments and suggestions, we have made the following changes in the revised manuscript:

1. The spatial resolution of E3SMv1 used for this study has been clarified in the abstract, conclusion, and other relevant places.

2. Additional information about the nudging implementation in E3SMv1 is added to Section 2.2.

3. A detailed description of the differences in emissions between pre-industrial (PI, year 1850) and present-day (PD, year 2010) simulations is added to Section 2.3 and the caption of Table S3 in the supplement.

4. Section 5 "Impact on the estimation of anthropogenic aerosol effect", has been revised and reorganized. New figures (12-14, A7, and A8) have been added to discuss: a) the impact of constraining data frequency on the effective aerosol forcing (F_{aer}) estimate, and b) the impact of the temperature nudging on the F_{aer} estimate in the nudged EAM simulations.

5. Typo corrections and writing improvement have been made throughout the manuscript.

The point-by-point responses to the reviewer's comments are presented below.

Reply to Referee 1

Referee comment: The EAMv1 nudging simulations are improved in this work. My major concern is the model resolution used in this work. The current model is configured to be 1 deg. It does not fully take advantage of reanalysis data with higher spatial resolution, which may dilute the impacts from ERAI and ERA5. On the other hand, if the model is configured to a higher spatial resolution (which is the direction in the global climate community), the model accuracy to simulation important small-scale processes could also be improved. In that case, it may require a different nudging strength or frequency.

Author response: For the current study, we focused on the analysis using the 1-deg model, because it's the standard resolution for v1 and v2 of E3SM (Golaz et al., 2019, Golaz et al., 2022) and is used for most model applications. But we agree with the reviewer that it would be useful to test the nudging implementation (e.g., relaxation time scale, frequency) at higher spatial resolutions (especially for 25km, which is close to the ERA5 resolution), so that we could maximize the benefit of using the high-resolution reanalysis data and improve the global atmospheric hindcast simulations.

We have made clarifications in the abstract, conclusion, and other relevant places to explicitly state that this study focuses on the E3SMv1 model that is configured with a 1-deg horizontal resolution.

Referee comment: Page 9, Figure 3, typo? No magenta box in Figure 4e. Maybe Figure 2e?

Author response: The correction has been made in the revised manuscript.

Referee comment: Page 21, line 350-351, there is no Table S3 in the Supplement.

Author response: There might be some technical issue. Table S3 in the original Supplement (https://gmd.copernicus.org/preprints/gmd-2022-10/gmd-2022-10-supplement.pdf) does show up on our computer. We have double-checked the Tables in Supplement in the revised submission.

Referee comment: Also, I'm confused about the sign between line 351 and in Figure 12. Suggest to clarify the discussion here.

Author response: Sorry for the confusion. Figure 12 illustrates the ratio of the values derived from the nudged simulation to the values derived from the CLIM simulation. As the signs of aerosol-induced effects from the nudged simulation and CLIM are the same, the ratio will always be positive. We have made revisions in Figure 12 and clarifications in Section 5 of the revised manuscript.

Referee comment: line 365-369, this is also a typical approach in many other earth system models.

Author response: We agree with the reviewer. This is addressed by adjusting the wording in Section 5 of the revised manuscript and cited the previous studies on many other earth system models:

"*Overall, consistent with previous studies using other global aerosol-climate models (e.g. Kooperman et al., 2012; Zhang et al., 2014; Ghan et al., 2016), our results indicate that nudging the horizontal winds but not temperature towards the ERA5 reanalysis or EAM's own meteorology is the preferred simulation configuration to estimate Faer. The temperature nudging needs to be applied with caution, as the potential climatology discrepancies between CLIM and reanalysis might lead to large biases in the Faer estimation.*"

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.

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.

Ghan, S., Wang, M., Zhang, S., Ferrachat, S., Gettelman, A., Griesfeller, J., Kipling, Z., Lohmann, U., Morrison, H., Neubauer, D., Partridge, D. G., Stier, P., Takemura, T., Wang, H., and Zhang, K.: Challenges in constraining anthropogenic aerosol effects on cloud radiative forcing using present-day spatiotemporal variability, Proceedings of the National Academy of Sciences, 113, 5804–5811, https://doi.org/10.1073/pnas.1514036113, 2016.

Reply to Referee 2

Referee comment: 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.

Author response: Thanks for the positive feedback and comments. Following the reviewer's suggestion, we have performed the nudged simulations with the 3-hourly nudging data and discussed the impact on the effective aerosol forcing (F_{aer}) estimate in Section 5:

In Figure 14, we evaluate the impact of the frequency of the constraining data. At least for the global and annual mean F_{aer}, the results obtained from simulations using 6-hourly constraining data (orange bars in the figure) are very similar to those obtained using 3-hourly constraining data (blue bars), regardless of whether UV-nudging (Fig. 14, upper row) or UVT-nudging (Fig.14, lower row) is used. The small impact of constraining data frequency on global and tropical mean F_{aer} estimates is expected. As shown in Section 3.2, the impact of constraining data frequency on present-day simulations is sizable only in limited regions where strong diurnal variations exist. Therefore, using 6-hourly constraining data in nudged simulations is sufficient for estimating the time-mean F_{aer}.

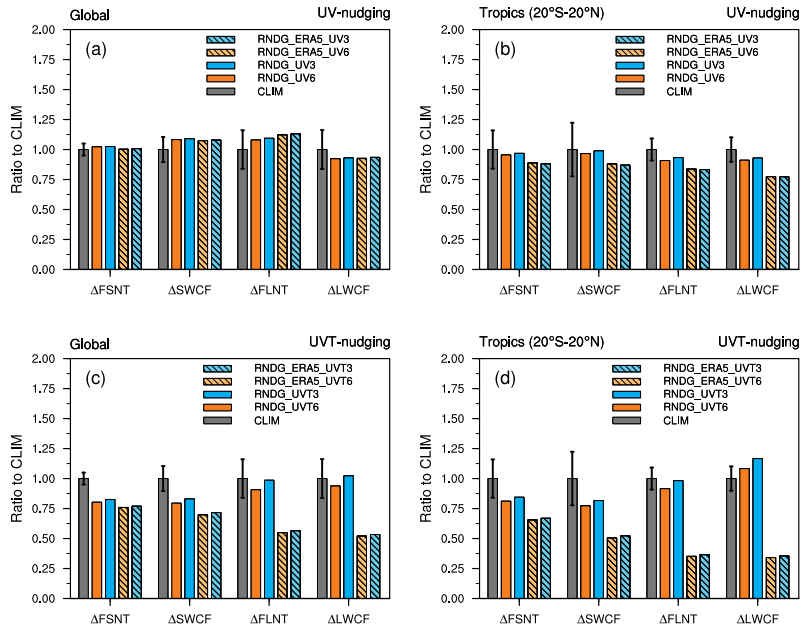

Figure 14. *Global mean (a, c) and topical mean (b, d) annually-averaged anthropogenic aerosol effect (PD-PI differences, denoted by Δ) estimated by free-running (i.e. CLIM, grey bars) and nudged EAM simulations (colored bars). FSNT and FLNT are the TOA net shortwave and longwave radiation flux, respectively. SWCF and LWCF are the shortwave and longwave cloud radiative forcing, respectively. All values have been normalized by the ensemble*

mean of CLIM. The thick whiskers attached to the grey bars indicate the two-standard-deviation ranges of the 5-member CLIM ensemble. The upper row compares the UV-nudged simulations with CLIM, and the lower row compares the UVT-nudged simulations with CLIM. The solid color bars indicate simulations nudged towards CLIM; the hatched color bars indicate simulations nudged towards ERA5 reanalysis. Orange and blue bars correspond to nudged simulations performed with 6-hourly and 3-hourly constraining data, respectively. The simulations are described in Section 2.3 and Table 1.

Referee comment: 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?

Author response: This is a good question. Our original statement is for the simulations nudged towards reanalysis. We do think the additional temperature nudging will constrain the meteorological adjustment to the aerosol perturbation, which will lead to a biased F_{aer} estimate even for the simulations nudged towards CLIM. We have added a new figure (A8) in the appendix and discussed it in Section 5:

Figure 12a–b indicates that when EAMv1 simulations are nudged to its own climatology, constraining temperature also has significant impacts on the estimated ΔFSNT and ΔSWCF (see green versus pink bars with solid fill). This is mainly due to the constrained temperature adjustment to the aerosol perturbation, since the PD and PI simulations were nudged towards the same CLIM PD simulation. The anthropogenic aerosols and precursors are known to have significant impacts on air temperature (Fig. A8a). When only the horizontal winds are nudged towards CLIM PD, the impacts of anthropogenic aerosols and precursors on temperature are smaller than in the free-running simulations but nevertheless still sizable (Fig. A8b). In contrast, the nudging of temperature substantially reduces the PD-PI temperature differences as expected (Fig. A8c). The results shown in Fig. A8 suggest that the constrained temperature response mainly affects the simulated PD-PI changes in cloud liquid mass (ΔCLDLIQ, Fig. A8, second row) and cloud ice mass (ΔCLDICE, Fig. A8, third row) in the middle and lower troposphere (i.e., below 500hPa). This explains why the solid green bars in Fig. 12 deviate from the gray bars more in the shortwave radiation than in the longwave component.

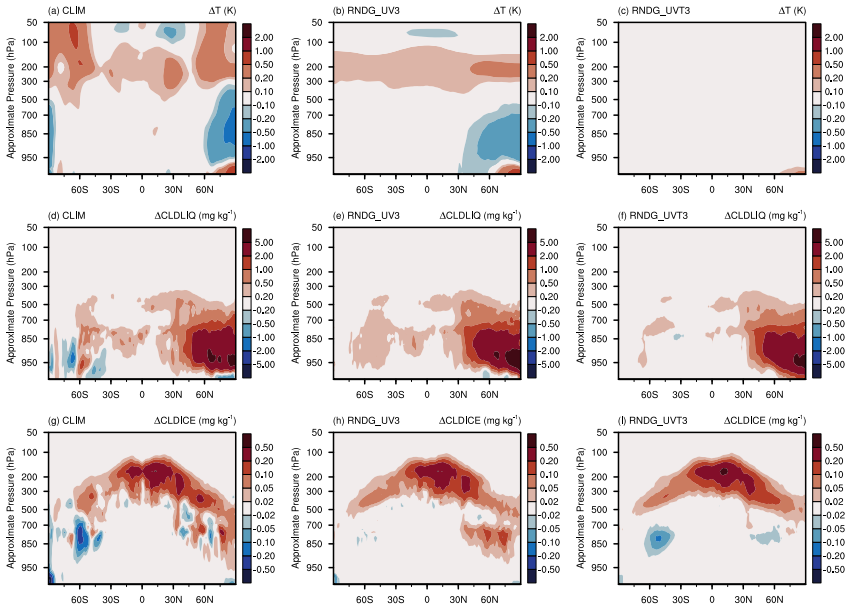

Figure A8. *PD-PI differences in temperature (ΔT, unit: K, top row), cloud liquid water mixing ratio (ΔCLDLIQ, unit: mg kg^{-1}, middle row) and cloud ice water mixing ratio (ΔCLDICE, unit: mg kg^{-1}, bottom row) from the free-running (i.e. CLIM) and nudged EAM simulations. RNDG_UVT3 (second column) is for wind-only nudging, and RNDG_UVT3 (third column) is for nudging to both wind and temperature fields. 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.*

We have also added two figures (13 and A7) in Section 5 to discuss the impact of temperature nudging on the simulations nudged towards ERA5 reanalysis:

Fig. 13a suggests that EAMv1's climatology, when compared to ERA5, features cold biases on the order of 1-2 K in the upper troposphere over the tropical and mid-latitude regions where small ice crystals are often formed through homogeneous ice nucleation. These small ice crystals are known to have a large impact on the simulated cloud radiative forcing. Nudging EAM's temperature towards ERA5 effectively introduces bias corrections (Fig 13b) that lead to a warmer base state and weakened homogeneous ice nucleation (Fig. A7b). Consequently, the PD-PI changes in aerosol and precursor emissions cause substantially smaller ΔICNIC compared to CLIM (Fig. 13d versus c), which explains the significant reduction in ΔFLNT and ΔLWCF shown as hatched green bars in Fig. 12a–b. This reasoning is consistent with the finding in Zhang et al. (2014) that temperature nudging in EAMv1's predecessor model CAM5 led to a substantial decrease in the ice cloud amount and a weaker impact of anthropogenic aerosols on longwave radiation.

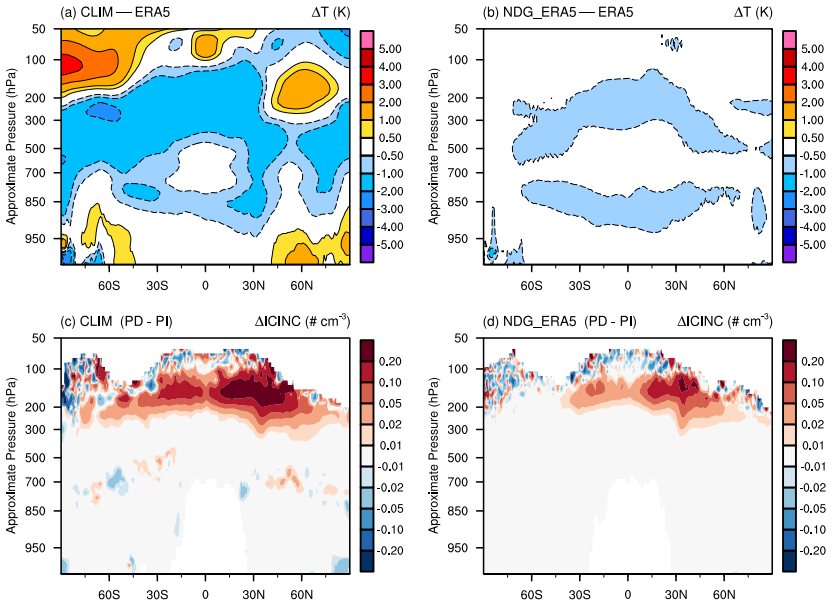

Figure 13. *Upper row: zonal and annual mean differences in temperature (ΔT, unit: K) between the CLIM PD simulation and the ERA5 reanalysis (panel a), and between a nudged PD simulation and ERA5 (panel b). The nudged simulation is labeled as "NDG_ERA5 (PD)" for brevity in panel b; it correspond to the simulation RNDG_ERA5_UVT3 in Table 1 performed with PD emissions of aerosols and precursors. Lower row: PD-PI differences of in-cloud ice number concentration (ΔICINC, unit: # cm^{-3}) derived from free-running (i.e. CLIM) simulations (panel c) and from EAMv1 simulations UVT-nudging towards ERA5 (i.e. RNDG_ERA5_UVT3, panel d). Details of simulation setup can be found in Sect. 2.3 and Table 1.*

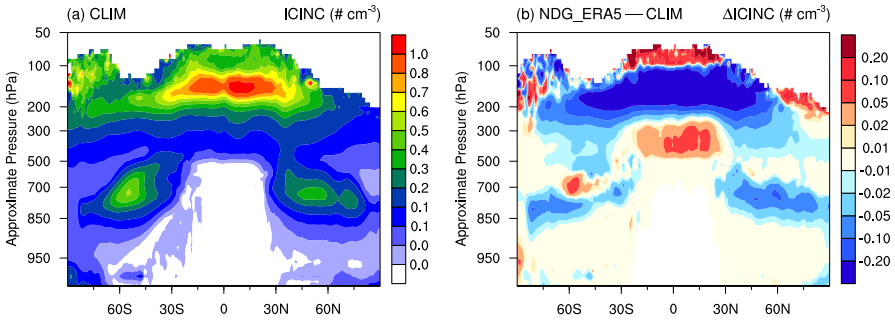

Figure A7. *Annual mean zonally averaged (a) in-cloud ice number concentration (ICINC, unit: # cm^{-3}) from EAMv1 free-running simula- tion (i.e., CLIM), and (b) difference in ICINC (ΔICINC, unit: # cm^{-3}) between CLIM and nudged EAMv1 simulation. The NDG_ERA5 in the figure caption is the acronym 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.*

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

Author response: Thank you for the question. The original nudging implementation in E3SMv1 was taken from CAM5.4, which calculates the nudging tendency after dynamics, but applies the nudging tendency after the physics parametrization suite (before the next call of the dynamical core). As a result, the nudging tendency plus the tendencies due to physics parameterizations

(i.e., physics tendency) will be diagnosed and applied as a forcing term in the physics-dynamics coupling calculation to update the model state variables (c.f. Zhang et al., 2018). In terms of time integration, this nudging implementation treats the nudging tendency and physics tendency in parallel (i.e., parallel splitting). 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:

Pink boxes in the left panel of Figure 1 illustrate where the nudging-related calculations occur in the default EAMv1. In a nudged simulation, after the resolved dynamics (see blue box in figure) have been calculated, a nudging tendency term in the form of Eq. (1) is calculated for each nudged variable with Xm being the value of X after the dynamical core. After the entire physics parameterization suite has been calculated, the sum of the parameterization-induced tendencies and the nudging tendencies are passed to the physics-dynamics coupling interface.

It is worth noting that, when an EAM simulation is considered to be a baseline simulation, the dynamical and thermodynam- ical variables (e.g., U, V, T, Q, and the surface pressure PS) that are archived – and subsequently used in a nudged simulation as the prescribed atmospheric state – are the values saved before the radiation calculation (cf. pink dashed box in Fig. 1a). In other words, in the default EAMv1, the Xp in the right-hand side of Eq. (1) is archived before radiation while the Xm in that same equation corresponds to the model state after the dynamical core. As is discussed in Section 3.1, the fact that Xp and Xm correspond to different locations in the time integration loop plays an important role in causing the issue in Sun et al. (2019) that motivated this study.

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.

Zhang, K., Rasch, P. J., Taylor, M. A., Wan, H., Leung, R., Ma, P.-L., Golaz, J.-C., Wolfe, J., Lin, W., Singh, B., Burrows, S., Yoon, J.-H., Wang, H., Qian, Y., Tang, Q., Caldwell, P., and Xie, S.: Impact of numerical choices on water conservation in the E3SM Atmosphere Model version 1 (EAMv1), Geoscientific Model Development, 11, 1971–1988, https://doi.org/10.5194/gmd-11-1971-2018, 2018.

Sun, J., Zhang, K., Wan, H., Ma, P.-L., Tang, Q., and Zhang, S.: Impact of Nudging Strategy on the Climate Representative- ness and Hindcast Skill of Constrained EAMv1 Simulations, Journal of Advances in Modeling Earth Systems, 11, 3911–3933, https://doi.org/10.1029/2019MS001831, 2019.

Referee comment: Line 154: Please define how CF is calculated.

Author response: cloud radiative forcing (CF) is defined as the sum of short-wave and long-wave radiative forcings. The definition has been added in Section 3 in the revised manuscript.

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

Author response: Thanks for the feedback.

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

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

To estimate the anthropogenic aerosol effect F_{aer}, pairs of simulations were conducted. Each pair had an identical experimental setup except that the emissions of aerosols and their precursor gases were set to the values of the year 2010 to represent the present-day (PD) condition in one simulation and the values of the year 1850 to represent the pre-industrial (PI) condition in the second simulation. The greenhouse gas concentrations, SST, and sea ice extent are unchanged (i.e., fixed at their year 2010 values). The main differences between PI and PD 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 from PD to PI conditions. Dust, sea salt, and marine organic aerosol emissions are calculated online using the surface wind speed and surface properties predicted in each simulation.

Referee comment: 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.

Author response: This is addressed in the response to the second Referee comment above.