Atmos. Chem. Phys. Discuss., 14, 10311–10343, 2014
www.atmos-chem-phys-discuss.net/14/10311/2014/
doi:10.5194/acpd-14-10311-2014
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Atmospheric Chemistry and Physics Discussions
Open Access

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Technical Note: On the use of nudging for aerosol-climate model intercomparison studies

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Received: 31 March 2014 – Accepted: 9 April 2014 – Published: 24 April 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Nudging is an assimilation technique widely used in the development and evaluation of climate models. Constraining the simulated wind and temperature fields using global weather reanalysis facilitates more straightforward comparison between simulation and observation, and reduces uncertainties associated with natural variabilities of the large-scale circulation. On the other hand, the forcing introduced by nudging can be strong enough to change the basic characteristics of the model climate. In the paper we show that for the Community Atmosphere Model version 5, due to the systematic temperature bias in the standard model and the sensitivity of simulated ice formation to anthropogenic aerosol concentration, nudging towards reanalysis results in substantial reductions in the ice cloud amount and the impact of anthropogenic aerosols on long-wave cloud forcing.

In order to reduce discrepancies between the nudged and unconstrained simulations and meanwhile take the advantages of nudging, two alternative experimentation methods are evaluated. The first one constrains only the horizontal winds. The second method nudges both winds and temperature, but replaces the long-term climatology of the reanalysis by that of the model. Results show that both methods lead to substantially improved agreement with the free-running model in terms of the top-of-atmosphere radiation budget and cloud ice amount. The wind-only nudging is more convenient to apply, and provides higher correlations of the wind fields, geopotential height and specific humidity between simulation and reanalysis. This suggests nudging the horizontal winds but not temperature is a good strategy for the investigation of aerosol indirect effects through ice clouds, since it provides well-constrained meteorology without strongly perturbing the model's mean climate.

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1 Introduction

Nudging (also called Newtonian relaxation) of meteorological fields towards estimates from weather analyses has been used in various studies concerning climate model development and evaluation (e.g., Jeuken et al., 1996; Feichter and Lohmann, 1999; Machenhauer and Kirchner, 2000; Ghan et al., 2001; Hauglustaine et al., 2004; Kerkweg et al., 2006; Schmidt et al., 2006; Telford et al., 2008; Kooperman et al., 2012). This technique introduces extra terms into the equations that govern the evolution of temperature, winds (equivalent to vorticity and divergence), and sometimes mass fields, to nudge them towards observed values. Nudging can be useful when developing and evaluating physical parameterizations and chemistry modules (e.g., van Aalst et al., 2004; Stier et al., 2005; Lohmann and Hoose, 2009; Jöckel et al., 2010; Zhang et al., 2012; Ma et al., 2013), because it strongly constrains some terms (e.g. advection) to be driven by observed meteorological events, meanwhile allows other terms (processes) described by physical parameterizations to evolve freely and drive the evolution of variables that are not being nudged. If the unconstrained terms approximate atmospheric processes reasonably, the resulting simulations should produce a simulation that can be compared to observation for specific weather episodes (Feichter and Lohmann, 1999; Dentener et al., 1999; Coindreau et al., 2007; Schulz et al., 2009; Roelofs et al., 2010). Because the meteorological features are strongly constrained, nudging eliminates one source of model variability, reduces error and uncertainty in other terms, and thus facilitates detection of signatures of changes in process representations (parameterizations) in simulations that might otherwise require multiple decades of simulation time in order to clearly discriminate between signal and noise (Lohmann and Hoose, 2009; Lohmann and Ferrachat, 2010; Kooperman et al., 2012). Because of these benefits, the AeroCom aerosol-climate model intercomparison initiative (http://aerocom.met.no/) explicitly requires nudged simulations for several projects of its Phase III activities on assessing the aerosol indirect effect (https://wiki.met.no/aerocom/indirect).

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The present paper is motivated by an AeroCom Phase III intercomparison that focuses on aerosol indirect effects through ice clouds (hereafter referred to as ice-AIE). The original experimental design required nudging both temperature and horizontal winds towards the ERA-Interim (Dee et al., 2011) reanalysis. When simulations were performed using the Community Atmosphere Model version 5 (CAM5, Neale et al., 2010), it was noticed that the top-of-atmosphere (TOA) radiation budget was substantially different from that of the unconstrained model. This implies the aerosol indirect effects estimated from the AeroCom ice-AIE experiments would differ from the standard (unconstrained) CAM5 estimates, and thus answers reported with this methodology would not be an accurate characterization of CAM5 behavior. Conducting the ice-AIE experiments without nudging, on the other hand, would cause difficulties in the evaluation against observation, and hinder the intercomparison with other models. In this work we carry out various sensitivity experiments to identify the cause of the discrepancies between the nudged and unconstrained simulations. We also test alternative nudging strategies to ensure resemblance between the simulated and observed large-scale circulation, and meanwhile avoid strongly perturbing the model's radiation balance. We believe the lessons learned using this study will also be useful to other modeling groups, and conclude by making recommendations about useful strategies for models that use nudging as an evaluation and verification framework.

The remainder of the paper is organized as follows: Sect. 2 briefly introduces the CAM5 model and describes the simulations. Section 3 investigates the impact of nudging on ice clouds and the TOA radiation budget. Section 4 evaluates two alternative nudging strategies. Section 5 summarizes the results and draws conclusions.

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2 Model and simulations

2.1 A brief overview of CAM5

In this study, we use CAM5.1 with the finite volume dynamical core at 1.9° latitude × 2.5° longitude resolution, 30 vertical layers, and the default 30 min time step. The modal aerosol module MAM3 (Liu et al., 2012) describes the tropospheric aerosol lifecycle, including various emission and formation mechanisms, microphysical processes, and removal mechanisms. MAM3 aerosols are composed of sulfate, black carbon, primary and secondary organic aerosols, sea salt, and mineral dust.

The stratiform cloud microphysics in CAM5.1 is represented by a two-moment parameterization (Morrison and Gettelman, 2008; Gettelman et al., 2008, 2010). Aerosols can directly affect the formation and properties of stratiform clouds by acting as cloud condensation nuclei (CCN) and ice nuclei (IN). Particles with mixed compositions that have high hygroscopicity provide sources for CCN, while dust-containing particles can act as IN. Ice particles can also form through the homogeneous freezing of aqueous sulfate aerosol solution. The ice nucleation parameterizations are described in Liu and Penner (2005); Liu et al. (2007) and Gettelman et al. (2010).

Representation of deep and shallow convection in CAM5 follows the work of Zhang and McFarlane (1995) and Park and Bretherton (2009), respectively. For the Zhang and McFarlane (1995) deep convection, although a two-moment microphysics scheme has been developed and evaluated (Song and Zhang, 2011; Song et al., 2012; Lim et al., 2014), it is not included in the model version used in this study. The moist turbulence is represented by the parameterization developed by Bretherton and Park (2009). Shortwave and longwave radiative transfer calculations are performed using the RRTMG code (Iacono et al., 2008; Mlawer et al., 1997). Further details of the model formulation are described in Neale et al. (2010).

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2.2 Nudging

The implementation of nudging used in this paper is the same as described by Kooperman et al. (2012). A tendency term of the form

$$-\frac{X_\mathrm{M} - X_\mathrm{P}}{\tau_X} \qquad (1)$$

is added to the prognostic equation of variable X where X stands for dry static energy (as a substitute for temperature) or horizontal winds. Subscript M indicates the model predicted value. Subscript P refers to the prescribed value, which can come from either the global weather reanalysis or a baseline CAM5 simulation performed without nudging. τ_X denotes the nudging time scale which can be variable dependent. In the study of Kooperman et al. (2012), a 6 h relaxation time was used for both temperature and winds and the model was nudged to the 6 hourly model output from a baseline CAM5 simulation.

Technically, the nudging term (Eq. 1) in CAM5 is applied as part of the "physics" tendency. It is used to update the model state variables after the moist processes and radiative transfer, and before the coupling of the atmosphere model with land and ocean (Fig. 1). For simulations that are nudged towards CAM5's own meteorology, the prior baseline simulation writes out the wind and temperature fields at the same location (dashed box in Fig. 1). Our experience revealed the location in the computation sequence is important, because choosing to archive the data at a location that differs from the point where nudging is applied can introduce an unintended forcing term that causes systematic differences in the simulated clouds, precipitation, and energy budget. This issue highlights the delicate balance of terms in the evolution equations, and the importance of a careful choice in the strategy used for nudging.

Later in the paper we will evaluate simulations that were nudged either to the ERA-Interim reanalysis or a CAM5 baseline simulation, and assess the impact of the temperature relaxation time τ_T. In addition, we will discuss a nudging strategy that replaces

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formula (Eq. 1) by

$$-\frac{X'_\mathrm{M} - X'_\mathrm{P}}{\tau_X}\,, \tag{2}$$

where X' denotes the anomaly of X with respect to its monthly mean climatology $\overline{X}$, i.e.,

$$X'_\mathrm{M} = X_\mathrm{M} - \overline{X}_\mathrm{M}\,, \tag{3}$$

$$X'_\mathrm{P} = X_\mathrm{P} - \overline{X}_\mathrm{P}\,. \tag{4}$$

The motivation for the anomaly nudging is that the original formula (Eq. 1) can be expressed as

$$-\frac{X_\mathrm{M} - X_\mathrm{P}}{\tau_X} = -\frac{(\overline{X}_\mathrm{M} + X'_\mathrm{M}) - (\overline{X}_\mathrm{P} + X'_\mathrm{P})}{\tau_X} \tag{5}$$

$$= -\frac{(X'_\mathrm{M} - X'_\mathrm{P})}{\tau_X} - \frac{(\overline{X}_\mathrm{M} - \overline{X}_\mathrm{P})}{\tau_X}\,. \tag{6}$$

When the model fields are nudged towards reanalysis, the first term on the right-hand side of Eq. (6) can be interpreted as a forcing term that relaxes the synoptic perturbations towards the observed episodes, which is the actual purpose of using nudging in the ice-AIE experiments. The scond term forces the model mean state towards the observed mean, correcting the biases in the model climatology. This is not intended by the AeroCom ice-AIE intercomparison.

The anomaly nudging Eq. (2) can be re-written as

$$-\frac{X'_\mathrm{M} - X'_\mathrm{P}}{\tau_X} = -\frac{X_\mathrm{M} - X^*_\mathrm{P}}{\tau_X} \tag{7}$$

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where

$$X_P^* = X_P - \overline{X}_P + \overline{X}_M \,. \tag{8}$$

This means the anomaly nudging can be implemented using a term that appears identical to expression (Eq. 1) but with X_P replaced by X_P^*. It thus requires only a pre-processing of the reanalysis data, without any change to the model source code.

2.3 Simulations

Following the protocol of the AeroCom III ice-AIE intercomparison, we carried out AMIP (Atmospheric Model Intercomparison Project, Gates et al., 1999) simulations for the years 2006 through 2010 after a three-month spin-up from October to December 2005. Concentrations of the greenhouse gases were set at the year 2000 observed values. For the anthropogenic and biomass burning emissions of aerosols and precursor gases, the year 2000 and 1850 fluxes of Lamarque et al. (2010) were used for the present-day (PD) and pre-industrial (PI) simulations, respectively. It should be clarified that, as intended by AeroCom, the PI simulations were conducted using the same greenhouse gas concentrations, sea surface temperature, and sea ice extent as in the PD simulations. The PD-PI differences are thus solely attributable to changes in the emission of aerosols and their precursor gases.

In order to provide a reference of the model's characteristic climatology under the standard configuration, we first performed a pair of PD and PI simulations with the free-running CAM (i.e., without nudging, referred to as the "CLIM" simulations in the remainder of the paper. cf. Table 1). A second pair of integrations followed the original ice-AIE protocol, in which both temperature and horizontal winds were nudged to the ERA-Interim reanalysis, with a 6 h relaxation time ("NDG_ERA_UVT"). To identify the cause of discrepancies between these two sets of simulations, we conducted simulations with u, v, and T nudged towards 6 hourly output from the PD CLIM case ("NDG_CLIM_UVT"). Several additional sensitivity simulations were conducted where the ERA-Interim reanalysis was used to prescribe the meteorology, but the value of τ_T

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was varied (e.g., “NDG_ERA_T1D”), or only part of the vertical domain was nudged (“NDG_ERA_UPPER” and “NDG_ERA_LOWER”). The wind-only (“NDG_ERA_UV”) and anomaly nudging (“NDG_ERA_UVTa”) were also applied and tested. A summary of the sensitivity simulations is provided in Table 1.

3 Temperature bias and ice nucleation

Kooperman et al. (2012) noted that nudging towards the ERA-Interim reanalysis led to non-negligible changes in the CAM5-simulated hydrological cycle, e.g., in the global mean precipitation rate and cloud water content. Our ice-AIE experiments indicate that nudging also leads to changes in the estimated aerosol indirect effects. Figure 2 shows the globally averaged 5 yr mean PD-PI differences in several quantities related to the TOA radiation budget. To facilitate a quantitative comparison, results from the nudged simulations have been normalized by the corresponding values derived from the CLIM simulations. Aerosol-induced changes in the TOA net shortwave radiation flux (ΔFSNT) and shortwave cloud forcing (ΔSWCF) are reasonably similar in the free-running and nudged simulations, with discrepancies being less than 25 % (Fig. 2a). For the long-wave radiation flux (ΔFLNT) and cloud forcing (ΔLWCF), however, results from the ERA-nudged simulations are about a factor of 4 smaller (Fig. 2b).

To understand this difference, we included in Fig. 2 the simulations that were nudged towards CAM5’s baseline simulation (blue bars). This setup did not produce small ΔFLNT and ΔLWCF. Rather, the PD-PI differences are slightly larger than in the free-running model (consistent with results of Kooperman et al., 2012), possibly because nudging the PD and PI simulations towards the same PD CLIM meteorology suppresses negative feedbacks from the large-scale circulation. The similarity between the nudged-to-baseline and free-running simulations, and the large contrast between them and the nudged-to-reanalysis simulations, suggest that the discrepancies in the climatology between CLIM and reanalysis probably play an important role here.

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Further investigation revealed that the differences are attributable to the temperature changes introduced by nudging towards reanalysis. Compared to the ERA reanalysis, the standard CAM5 model has a general cold bias throughout the whole vertical domain, as can be seen from the zonal and annual mean temperature differences in Fig. 3a. The same features are revealed in a comparison with the NCEP (Kanamitsu et al., 2002) and MERRA (Rienecker et al., 2011) reanalyses (Fig. 3b and c). Nudging towards reanalysis introduces a correction term in the thermodynamic equation (cf. Eq. 6, second term) and makes the simulated atmosphere warmer. The higher temperature, and the associated lower relative humidity, significantly reduce the frequency of occurence of homogeneous ice nucleation (Fig. 4), causing considerable decreases in ice crystal concentration in the upper troposphere. Because homogeneous ice nucleation on sulfate is a main mechanism for aerosols to influence the LWCF in CAM5, the reduced nucleation frequency leads to deceases in ΔFLNT and ΔLWCF.

To verify the reasoning described above, a group of sensitivity simulations were conducted with weaker nudging for temperature. As the relaxation time τ_T increases, the temperature climatology becomes closer to that in the free-running model (i.e., colder). More ice crystals are produced (Fig. 5a), and the PD-PI differences of LWCF increase (Fig. 5b). A trend of convergence with respect to τ_T can be seen in the results.

Although the simulations with varied τ_T confirm the relationship between temperature nudging and ΔLWCF, they do not verify whether the underlying mechanism is indeed the sensitivity of ice nucleation to ambient temperature. One could imagine, for example, that nudging temperature in the near surface levels might affect convection, and consequently the vertical transport of water vapor, which might affect humidity in the upper troposphere and hence the formation of ice clouds. To find out whether this is the case, we conducted additional simulations in which the temperature nudging was applied only to the lower or upper 15 levels of the model. The interface between levels 15 and 16 corresponds roughly to the 300 hPa pressure level. In Fig. 6, the global mean upper-troposphere (100–300 hPa) ice crystal number concentration (Fig. 6a) and global mean convective precipitation rate (Fig. 6b) are shown as indices for ice forma-

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tion and convective activity, respectively. Compared to the CLIM simulation, nudging temperature in the middle and lower troposphere leads to a substantial reduction of convective precipitation but no reduction in the ice crystal amount. In contrast, nudging the upper troposphere (NDG_ERA_UPPER) has a relatively small impact on convective precipitation, but strongly affects the ice crystal number concentration. The low ice crystal number concentration in the NDG_ERA_UVT simulation ("ALL" in Fig. 6) can not be explained by the changed convective transport of water vapor due to temperature nudging in the lower troposphere. Rather, it is mainly a response to changes in upper-troposphere temperature.

Having clarified the impact of temperature biases on ice cloud formation and ice-AIE in CAM5, ideally one should try to identify the cause of the biases then improve the model. This is, however, difficult to achieve in short term. Under the assumption that the temperature climatology in CAM5 will stay unchanged until a major model upgrade, one needs to decide how to carry out the AeroCom ice-AIE experiments. For the purpose of evaluating and developing parameterizations for aerosols and ice clouds, using the observation constrained meteorology ensures that the parameterizations operates under "correct" meteorology. However, for the purpose of assessing the state of the art in global aerosol modeling, understanding uncertainties in the projected future climate change, and providing useful information for other applications of the same model, it is preferable for the nudged CAM5 simulations to retain the characteristics of the free-running model. We therefore explored a different experiment design for the ice-AIE experiments.

4 Alternative nudging strategies

Since the temperature nudging produces signatures that differ from the free-running CAM5 simulations, one might consider applying nudging to winds only, or use the anomaly nudging described in Sect. 2.2. In Fig. 7 the zonal and annual mean temperature simulated with the two methods are compared with the free-running CAM5 and the

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ERA reanalysis. As expected, the zonal mean temperature resulting from the anomaly nudging (NDG_ERA_UVTa) stays close to the unconstrained climatology (Fig. 7a), and is colder than reanalysis (Fig. 7b). The zonal mean temperature from the wind-only nudging is closer to that of the CLIM simulation between 30° S and 30° N, and more similar to the reanalysis in the middle and high latitudes (Fig. 7d). The different behaviors in the low vs. middle and high latitudes can be explained by the thermal wind relationship and the latitudinal variation of the Coriolis force.

Both the wind-only nudging and the anomaly nudging have potential issues. For the wind-only approach, a concern is that the inconsistency between mechanical and thermal forcing might induce a spurious circulation. As for the anomaly nudging, the synoptic perturbations derived from the reanalysis might be inconsistent with the monthly mean climatology of the free-running model, thus also triggering spurious circulations. To evaluate the two methods in this regard, Fig. 8 compares the correlation between the simulated weather patterns with those in the reanalysis. For each variable and pressure level shown here, the correlation coefficient was computed from 6 hourly instantaneous data, with the corresponding monthly climatology removed. The original experimental design (NDG_ERA_UVT) is included as a reference. The year 2006 is presented here as an example. The same features have been seen in the other years (not shown).

On the whole, the wind and temperature anomalies in the nudged simulations agree quite well with those in the reanalysis, with correlation coefficients exceeding 0.9 on most vertical levels (Fig. 8a–c). The original method gives highest correlations for all three variables (u, v, T). Between the two alternative approaches, the wind-only nudging results in slightly higher correlations for wind, and comparable results for temperature. These are understandable from the experimental design. For the geopotential height and specific humidity which are not directly constrained by the reanalysis, results obtained with wind-only nudging are better. This is especially true for humidity, possibly because the more realistic wind fields lead to better representation of the large-scale transport of water vapor.

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In Fig. 9 the aerosol-induced changes in TOA radiation fluxes and cloud forcing are presented for the alternative nudging strategies. Compared with the original method (NDG_ERA_UVT, green bars in Fig. 2), the results are substantially improved. This is especially true for the simulations using wind-only nudging, in which both the longwave and shortwave fluxes agree within 15 % with the references (CLIM). The anomaly nudging also produces signatures in aerosol forcing that are closer to the parent model, although the discrepancies with CLIM are slightly larger than those produced by the wind-only nudging. The PD-PI differences in FSNT and SWCF are about 25 % smaller than in the free-running model. Figures 8 and 9 and Tables A1 and A2 indicate that the wind-only nudging is able to provide well-constrained model meteorology and meanwhile retain the original characteristics of the CAM5 climatology in terms of the TOA radiation budget and the hydrological cycle. It is also more convenient to apply in comparison with the anomaly nudging. Therefore, at least for carrying out the AeroCom ice-AIE experiments with CAM5, nudging the simulated horizontal winds but not temperature towards the ERA-Interim reanalysis is our preferred experimental setup.

5 Conclusions

In this paper we discussed the impact of nudging in characterizing the aerosol indirect effects in CAM5. The motivation for using nudging in such an investigation is to force the simulated large-scale circulation to stay close to observations of a particular time period, to reduce uncertainties associated with natural variabilities in the large-scale flow, and facilitate comparison with results from other models that participate in the AeroCom Phase III activities. However, the existence of systematic biases in the model can compromise the strategy because nudging introduces a forcing that attempts to correct the biases, hence changing the model's response to anthropogenic aerosols.

When nudging is allowed to remove the temperature biases in CAM5, the frequency of cloud ice formation decreases significantly in the upper troposphere. This further leads to considerably smaller estimates of the anthropogenic aerosol impact on long-

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wave cloud forcing (LWCF), since homogeneous ice nucleation on sulfate is a main mechanism for aerosols to influence the LWCF in CAM5. Although simulations nudged towards the ERA-Interim reanalysis appear more realistic in some ways, process balances governing the model climate are no longer the same, making the results less useful for interpreting the behavior of the original model.

To resolve this issue, two alternative nudging approaches were tested. The first one applied nudging only to the horizontal winds from the ERA-Interim reanalysis, while the second method constrains both winds and temperature, but the reference meteorology was a combination of the climatology of CAM5 and the synoptic perturbations from the reanalysis. Evaluation indicated that in comparison with the original nudging strategy, the two methods led to substantially improved agreement with the free-running model in terms of the TOA radiation budget and cloud ice amount. Both methods were able to ensure high correlations between the simulated synoptic perturbations and those in the reanalysis. The wind-only nudging provided slightly more realistic results for the specific humidity and geopotential height, and led to estimates of the aerosol induced (PD-PI) cloud forcing changes that agreed better with those in the standard CAM5. It is also more convenient to apply than the anomaly nudging. We thus came to the conclusion that the wind-only nudging is a better strategy for the ice-AIE experiments for the CAM5 model.

Although this study focused on one model only, similar impact of temperature nudging on longwave cloud forcing probably also exist in other models that have systematic temperature bias, and use ice cloud parameterizations that are sensitive to aerosol concentrations. Based on this conclusion, a decision was made at the 12th AeroCom workshop (September 2013, Hamburg, Germany) that the phase III intercomparisons of aerosol indirect effects should use the wind-only nudging instead of the originally recommended wind-and-temperature nudging.

More generally, we have shown that the forcing introduced by nudging towards reanalysis can be strong enough to significantly change the basic characteristics of the model climate, making the results less useful for the purpose of interpreting the behav-

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ior of the original model. The relaxation technique needs to be applied with care. Between wind and temperature nudging, the latter may cause more issues because there are a number of temperature and relative humidity thresholds related to the phase change of water and the onset of various microphysical processes. Mathematically, these thresholds correspond to discontinuities. Technically, they show up in conditional expressions in the models codes that lead to branching of the calculation. As a result, even a small change in temperature may lead to considerable differences in the simulated mean state and/or in the balance between processes. Wind nudging is less of a problem, except that it may affect the emissions of dust and sea salt (e.g. Timmreck and Schulz, 2004; Astitha et al., 2012) which are often parameterized with a threshold of the near-surface wind speed, or make a difference to the land/ocean surface process. Our results indicated that the wind-only nudging not only provides very good correlations (between model simulation and reanalysis) for the large-scale dynamical fields such as wind itself and geopotential height, but also indirectly improves the simulated specific humidity (possibly because of the large-scale transport). It thus seems a better choice to apply the wind-only nudging instead of the widely used wind-and-temperature nudging, at least for model intercomparison studies that focus on aerosol effects on cold clouds.

Acknowledgements. We thank David Neubauer (ETH), Minghuai Wang, Heng Xiao, and Yang Gao (PNNL) for helpful discussions. We acknowledge the use of computational resources (ark:/85065/d7wd3xhc) at the NCAR-Wyoming Supercomputing Center provided by the National Science Foundation and the State of Wyoming, and supported by NCAR's Computational and Information Systems Laboratory. K. Zhang, X. Liu, S. Ghan, P.-L. Ma, and P. J. Rasch were supported by the Office of Science of US Department of Energy as part of the Earth System Modeling Program and the Scientific Discovery Through Advanced Computing (SciDAC) Program. H. Wan is grateful for the support of the Linus Pauling Distinguished Postdoctoral Fellowship of the Pacific Northwest National Laboratory (PNNL) and the PNNL Laboratory Directed Research and Development Program. PNNL is a multiprogram laboratory operated for DOE by Battelle Memorial Institute under contract DE-AC05-76RL01830. G. J. Kooperman was supported by the Center for Multiscale Modeling of Atmospheric Processes (www.cmmap.org),

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a National Science Foundation, Science and Technology Center under Cooperative Agreement ATM-0425247, through sub-awards to Richard Somerville and John Helly.

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Table 1. List of CAM5 simulations. τ_U, τ_V, τ_T are the relaxation time scales for zonal wind, meridional wind, and temperature, respectively. TL refers to the vertical levels (given as indices counting from model top) on which temperature nudging was applied. The interface between model levels 15 and 16 roughly corresponds to the 300 hPa pressure level. Details of the experimental setup are described in Sect. 2.3.

Simulation	τ_U	τ_V	τ_T	TL	Description	Cf. Section
CLIM	–	–	–	–	Reference simulation without nudging	Sects. 3 and 4
NDG_CLIM_UVT	6 h	6 h	6 h	All	Nudged towards the present-day CLIM simulation	Sects. 3 and 4
NDG_ERA_UVT	6 h	6 h	6 h	All	Nudged towards ERA-Interim reanalysis	Sect. 3
NDG_ERA_T1D	6 h	6 h	1 day	All	Nudged towards ERA-Interim reanalysis	Sect. 3
NDG_ERA_T4D	6 h	6 h	4 days	All	Nudged towards ERA-Interim reanalysis	Sect. 3
NDG_ERA_T16D	6 h	6 h	16 days	All	Nudged towards ERA-Interim reanalysis	Sect. 3
NDG_ERA_T64D	6 h	6 h	64 days	All	Nudged towards ERA-Interim reanalysis	Sect. 3
NDG_ERA_UPPER	6 h	6 h	6 h	1–15	Nudged towards ERA-Interim reanalysis	Sect. 3
NDG_ERA_LOWER	6 h	6 h	6 h	16–30	Nudged towards ERA-Interim reanalysis	Sect. 3
NDG_ERA_UV	6 h	6 h	–	–	Nudged towards ERA-Interim reanalysis	Sect. 4
NDG_ERA_UVTa	6 h	6 h	6 h	All	Anomaly nudging using Eqs. (7) and (8)	Sect. 4

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Table A1. Global mean metrics in free-running and nudged present-day simulations. Meanings of the acronyms are: SWCF: shortwave cloud forcing; LWCF: longwave cloud forcing; CF: total cloud forcing; LWP: liquid water path; IWP: ice water path; PRECT: total precipitation rate; PRECL: large-scale precipitation rate; PRECC: convective precipitation rate; AOD: aerosol optical depth at 550 nm wavelength. All results are given as 5 yr (2006–2010) average ± one standard deviation of the annual mean.

Simulation	SWCF (Wm^{-2})	LWCF (Wm^{-2})	CF (Wm^{-2})	LWP (gm^{-2})	IWP (gm^{-2})	PRECT ($mm d^{-1}$)	PRECL ($mm d^{-1}$)	PRECC ($mm d^{-1}$)	AOD (Unitless)
CLIM	−52.4 ± 0.51	23.9 ± 0.06	−28.5 ± 0.54	45.5 ± 0.69	17.6 ± 0.10	2.99 ± 0.02	0.88 ± 0.005	2.11 ± 0.02	0.121 ± 0.001
NDG_CLIM_UVT	−51.8 ± 0.48	23.7 ± 0.11	−28.1 ± 0.48	45.2 ± 0.83	17.7 ± 0.12	3.00 ± 0.02	0.88 ± 0.020	2.11 ± 0.02	0.122 ± 0.002
NDG_ERA_UVT	−53.3 ± 0.53	19.7 ± 0.15	−33.6 ± 0.48	53.4 ± 0.52	15.9 ± 0.22	2.66 ± 0.02	0.89 ± 0.01	1.77 ± 0.02	0.127 ± 0.001
NDG_ERA_UV	−53.3 ± 0.42	24.4 ± 0.22	−28.8 ± 0.60	46.5 ± 0.80	17.3 ± 0.19	3.00 ± 0.02	0.89 ± 0.015	2.11 ± 0.01	0.122 ± 0.002
NDG_ERA_UVTa	−50.7 ± 0.29	24.3 ± 0.52	−26.4 ± 0.30	42.5 ± 0.26	18.0 ± 0.45	2.87 ± 0.04	0.87 ± 0.01	1.99 ± 0.05	0.129 ± 0.001

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Table A2. As in Table A1 but for the aerosol induced changes (PD-PI differences, denoted by Δ). FNET stands for the TOA net radiation flux.

Simulation	ΔFNET ($W m^{-2}$)	ΔFSNT ($W m^{-2}$)	ΔFLNT ($W m^{-2}$)	ΔFLNTC ($W m^{-2}$)	ΔSWCF ($W m^{-2}$)	ΔLWCF ($W m^{-2}$)	ΔCF ($g m^{-2}$)	ΔLWP ($g m^{-2}$)	ΔIWP ($g m^{-2}$)	ΔAOD (Unitless)
CLIM	−1.38 ± 0.14	−2.14 ± 0.08	0.76 ± 0.16	0.18 ± 0.15	−1.76 ± 0.18	0.58 ± 0.02	−1.27 ± 0.12	3.61 ± 0.15	0.17 ± 0.05	0.0148 ± 0.0011
NDG_CLIM_UVT	−1.20 ± 0.05	−2.01 ± 0.07	0.80 ± 0.06	0.06 ± 0.00	−1.69 ± 0.07	0.80 ± 0.06	−0.94 ± 0.05	3.45 ± 0.16	0.35 ± 0.03	0.0155 ± 0.0001
NDG_ERA_UVT	−1.48 ± 0.04	−1.70 ± 0.03	0.22 ± 0.02	0.07 ± 0.01	−1.33 ± 0.03	0.15 ± 0.01	−1.18 ± 0.04	3.70 ± 0.12	0.05 ± 0.01	0.0175 ± 0.0001
NDG_ERA_UV	−1.40 ± 0.06	−2.07 ± 0.04	0.67 ± 0.03	0.15 ± 0.01	−1.72 ± 0.04	0.52 ± 0.03	−1.20 ± 0.05	3.50 ± 0.09	0.13 ± 0.02	0.0155 ± 0.0002
NDG_ERA_UVTa	−1.05 ± 0.03	−1.90 ± 0.02	0.85 ± 0.01	0.08 ± 0.01	−1.58 ± 0.02	0.77 ± 0.01	−0.81 ± 0.02	3.01 ± 0.04	0.36 ± 0.01	0.0159 ± 0.0002

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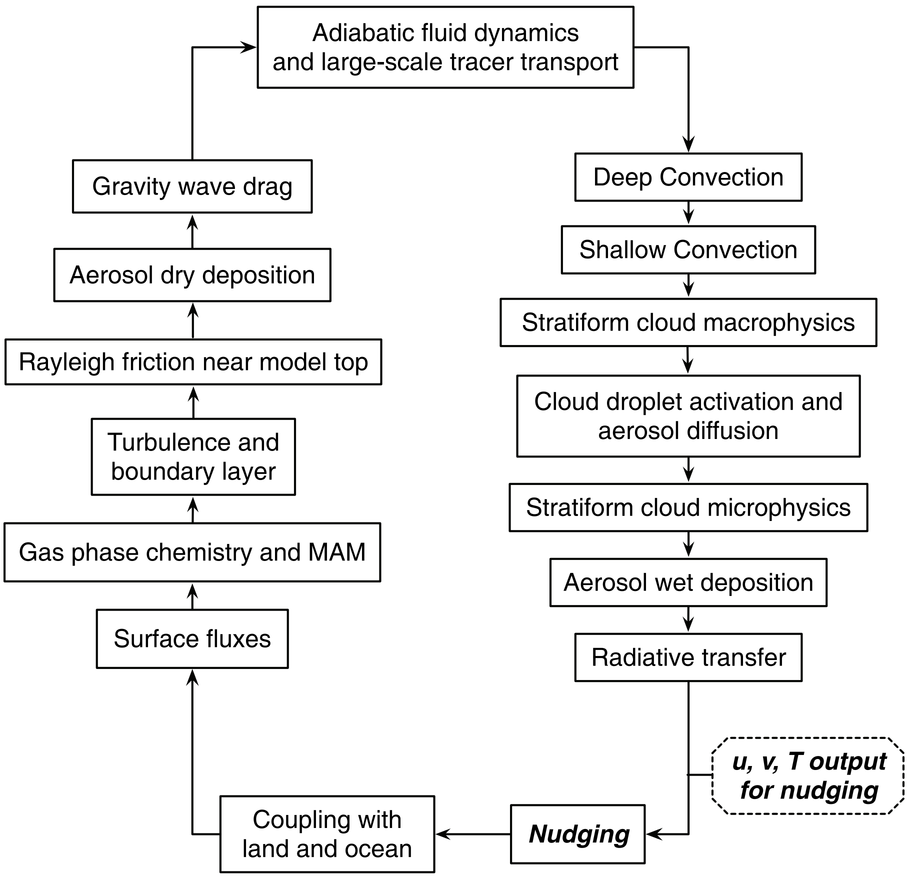

Fig. 1. Flowchart showing the implementation of nudging in the computing sequence of the CAM5 model.

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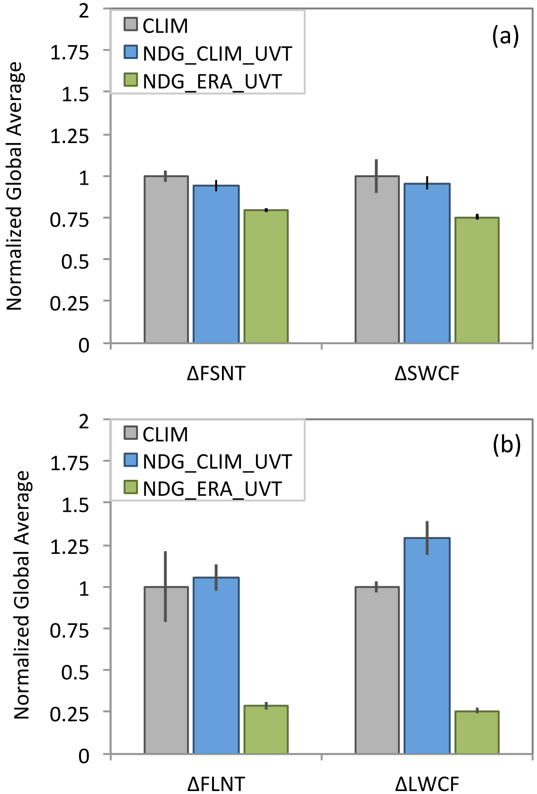

Fig. 2. Normalized global mean 5 yr mean PD-PI differences (Δ) in **(a)** the TOA net shortwave radiation flux (FSNT) and shortwave cloud forcing (SWCF), and **(b)** the TOA net longwave radiation flux (FLNT) and longwave cloud forcing (LWCF). The thin vertical line associated to each bar indicates the standard deviation of the annual average. Results from the nudges simulations (NDG_CLIM_UVT and NDG_ERA_UVT) are normalized by the corresponding 5 yr average PD-PI differences from the unconstrained (CLIM) simulations. Details of the experimental setup are explained in Sect. 2.3 and Table 1.

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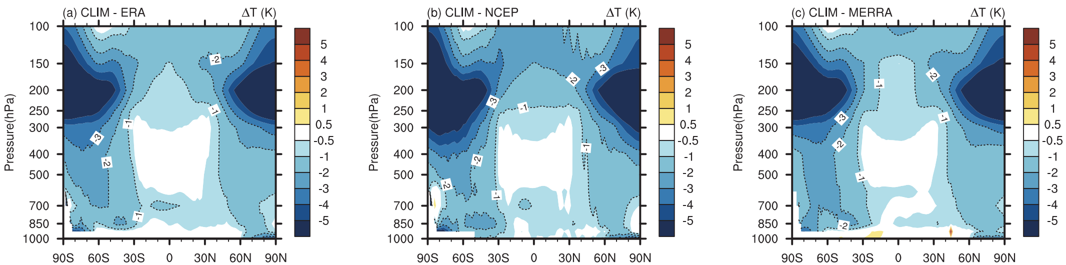

Fig. 3. Zonally averaged 5 yr (2006–2010) mean differences between temperature simulated by the free-running CAM5 (“CLIM”) and the **(a)** ERA-Interim, **(b)** NCEP, **(c)** MERRA reanalyses. Units: K.

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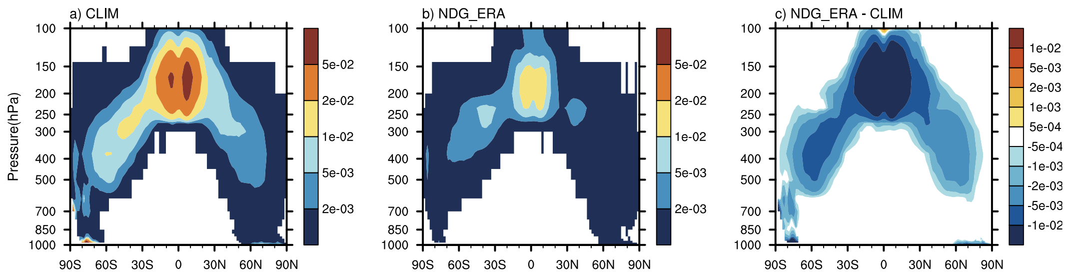

Fig. 4. Zonal and 5 yr mean frequency of occurrence of the homogeneous ice nucleation in the CLIM and NDG_ERA_UVT simulations, and the difference. Both simulations used present-day (PD) aerosol emissions.

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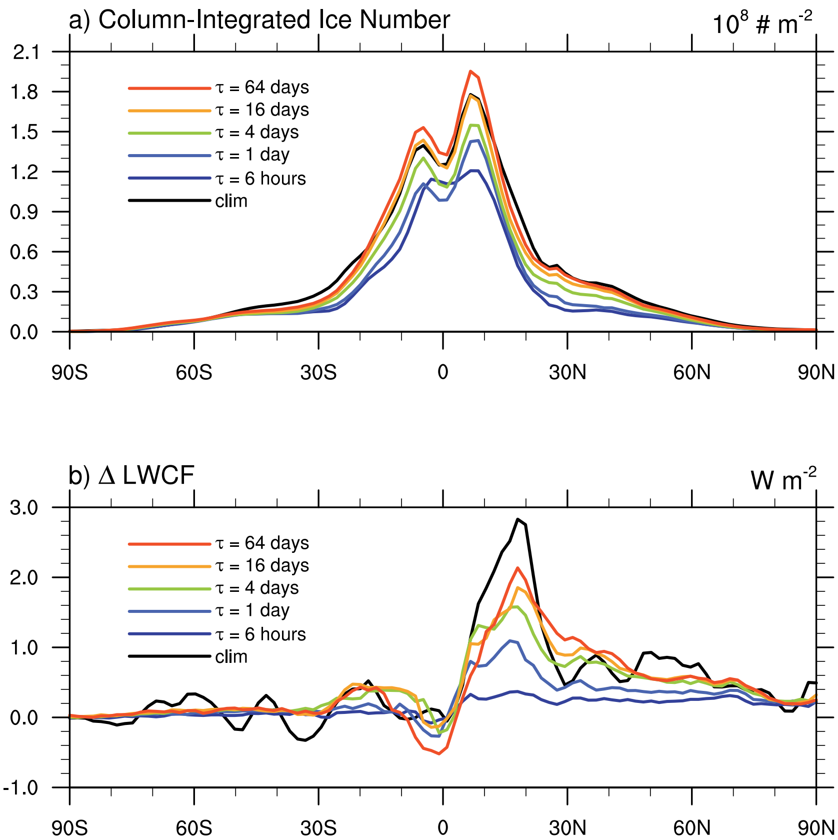

Fig. 5. Sensitivity of zonal and annual mean **(a)** present-day ice crystal number concentration in the upper troposphere (vertical integral between 100 hPa and 300 hPa, unit: $10^8\ m^{-2}$), and **(b)** aerosol induced longwave cloud forcing change (PD-PI, unit: $W\,m^{-2}$), to the temperature relaxation time scale τ_T in CAM5 simulations where temperature and horizontal winds were nudged towards the ERA-Interim reanalysis.

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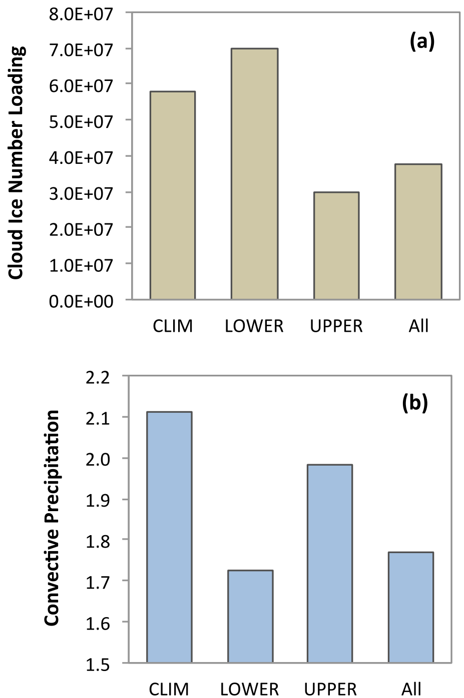

Fig. 6. (a) Global mean cloud ice number loading between 100 hPa and 300 hPa (units: m^{-2}), and **(b)** global mean convective precipitation rate (mm day^{-1}), in various simulations using present-day aerosol and precursor gas emissions. CLIM: without nudging; LOWER: temperature was nudged towards the ERA-Interim analysis in the lower 15 levels (roughly from 300 hPa to the surface, NDG_ERA_LOWER in Table 1); UPPER: temperature was nudged towards the ERA-Interim analysis in the upper 15 levels (roughly from model top to 300 hPa, NDG_ERA_UPPER in Table 1); All: temperature on all model levels was nudged towards ERA-Interim (NDG_ERA_UVT in Table 1). In the latter three simulations, horizontal winds were nudged towards ERA-Interim on all levels. The nudging time scale, when applicable, was 6 h. Details of the experimental setup are explained in Sect. 2.3 and Table 1.

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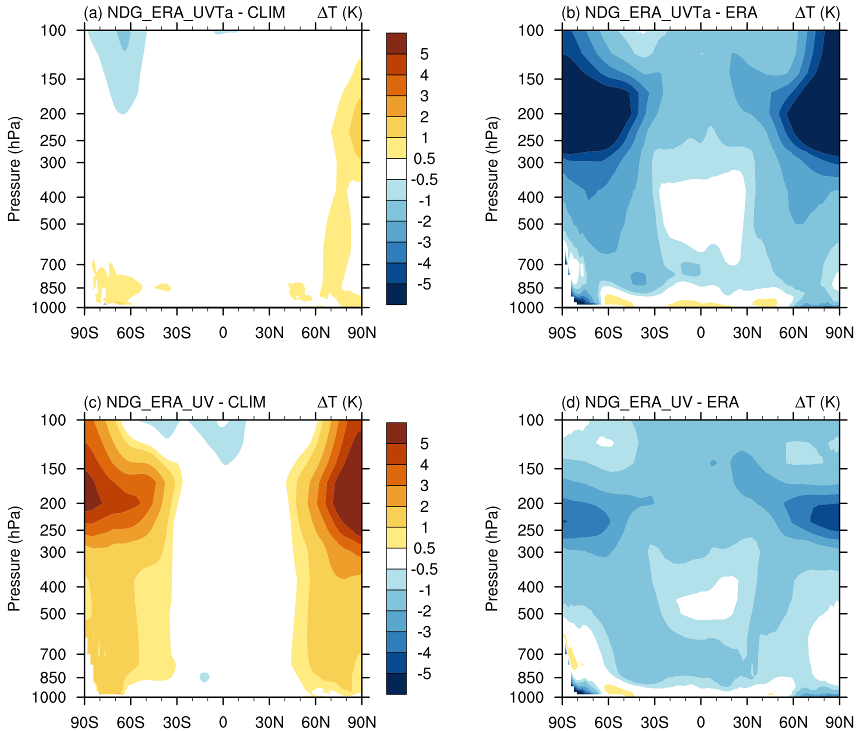

Fig. 7. Left column: 5 yr (2006–2010) mean zonal mean temperature differences between nudged and free-running CAM5 simulations. Right column: same as left column but between nudged simulations and the ERA-Interim reanalysis. Simulations shown in the upper and lower rows used the anomaly nudging described in Sect. 2.2 (NDG_ERA_UVTa) and the wind-only nudging (NDG_ERA_UV), respectively.

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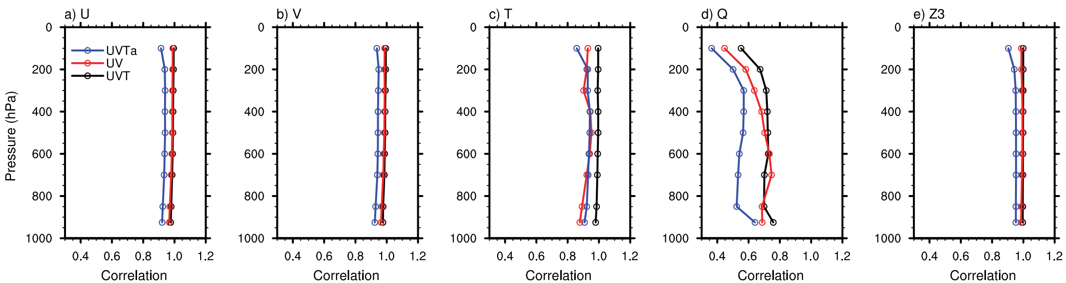

Fig. 8. Anomaly correlation between horizontal winds, temperature, specific humidity and geopotential height in the nudged simulations and those in the ERA-Interim reanalysis. The correlation coefficients were computed from 6 hourly instantaneous data on pressure levels, with the corresponding monthly climatology removed.

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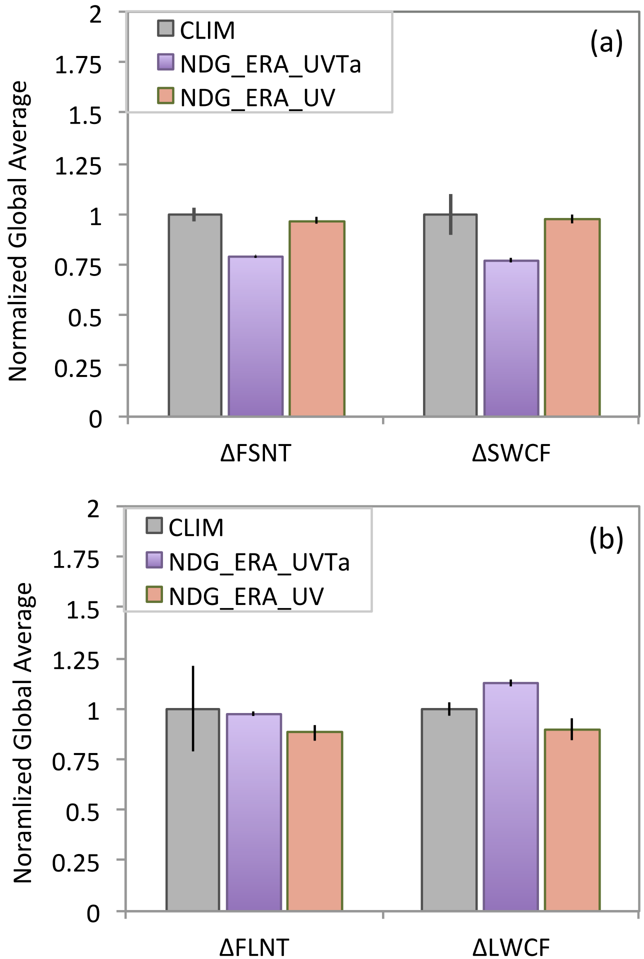

Fig. 9. As in Fig. 2 but comparing two alternative nudging strategies (NDG_ERA_UVTa and NDG_ERA_UV) with the free-running model (CLIM).

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