Changing the Climate Sensitivity of an Atmospheric General Circulation Model through Cloud Radiative Adjustment

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(Manuscript received 11 October 2011, in final form 6 March 2012)

ABSTRACT

Conducting probabilistic climate projections with a particular climate model requires the ability to vary the model's characteristics, such as its climate sensitivity. In this study, the authors implement and validate a method to change the climate sensitivity of the National Center for Atmospheric Research (NCAR) Community Atmosphere Model, version 3 (CAM3), through cloud radiative adjustment. Results show that the cloud radiative adjustment method does not lead to physically unrealistic changes in the model's response to an external forcing, such as doubling CO_2 concentrations or increasing sulfate aerosol concentrations. Furthermore, this method has some advantages compared to the traditional perturbed physics approach. In particular, the cloud radiative adjustment method can produce any value of climate sensitivity within the wide range of uncertainty based on the observed twentieth century climate change. As a consequence, this method allows Monte Carlo–type probabilistic climate forecasts to be conducted where values of uncertain parameters not only cover the whole uncertainty range, but cover it homogeneously. Unlike the perturbed physics approach that can produce several versions of a model with the same climate sensitivity but with very different regional patterns of change, the cloud radiative adjustment method can only produce one version of the model with a specific climate sensitivity. As such, a limitation of this method is that it cannot cover the full uncertainty in regional patterns of climate change.

1. Introduction

For many years, the Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Global Change has approached the issue of uncertainty in climate change by estimating the probability distribution functions (PDFs) of each uncertain input controlling human emissions and the climate response (Reilly et al. 2001; Forest et al. 2001, 2008). Then probabilistic climate projections are performed based on these PDFs (Sokolov et al. 2009; Webster et al. 2011). But conducting probabilistic climate projections with a particular climate model requires the ability to vary the model's characteristics, such as its climate sensitivity (CS). A number of studies aimed at obtaining versions of a model with different values of climate sensitivity have been carried out recently with different atmosphere–ocean general circulation models

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DOI: 10.1175/JCLI-D-11-00590.1

(AOGCMs) using a perturbed physics approach (Murphy et al. 2004; Stainforth et al. 2005; Collins et al. 2006; Webb et al. 2006; Yokohata et al. 2010; Sanderson 2011). The range of climate sensitivity generated in most of these studies, however, does not cover the range obtained based on the observed twentieth-century climate change (Knutti et al. 2003; Forest et al. 2008). Moreover, in most cases, the values of climate sensitivity obtained by the perturbed physics approach tend to cluster around the climate sensitivity of the unperturbed version of the given model.

Hansen et al. (1993) proposed a method to change climate sensitivity by artificially changing the cloud feedback. The choice of cloud feedback seems very natural because differences in climate sensitivity between different AOGCMs are primarily caused by large differences in this feedback (Cess et al. 1990; Colman 2003; Bony et al. 2006; Webb et al. 2006; Williams et al. 2006). This approach was extensively tested in simulations with the MIT 2D (zonally averaged) climate model (Sokolov and Stone 1998). It was shown that using a cloud radiative adjustment method to change the model's climate sensitivity does not lead to physically unrealistic changes in the model's response to an external forcing. In particular,

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the dependency of the changes in the components of the global mean surface energy balance on changes in surface air temperature is very similar to that seen in simulations with different AOGCMs (Sokolov 2006). The approach was also used in recent simulations with the Goddard Institute for Space Studies (GISS) AOGCM (Hansen et al. 2002), but limited to two values of climate sensitivity: $CS = 2.0^{\circ}C$ and $CS = 4.0^{\circ}C$.

The algorithm for changing the cloud feedback was implemented in the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3). The goal of this study is to demonstrate that varying the model's climate sensitivity through cloud radiative adjustment does not lead to a physically unrealistic response of the climate system to an external forcing. Regional patterns of change in different climate variables are rather different in different GCMs. For example, regional changes in precipitation simulated by different models have not only different magnitudes, but often different signs. Because of that, the ideal case for our purpose is to use just one AOGCM. This way it is possible to make a direct comparison between the changes in the climate response caused by perturbing the model's physical parameters and the changes caused by adjusting clouds. Unfortunately, CAM3 is rather insensitive to the perturbed physics approach (Sanderson 2011). For example, we were only able to vary the climate sensitivity of CAM (at T21 spectral truncation) between 2.0° and 3.0°C.

In this study, we first compare results of equilibrium and transient climate change simulations with CAM3 in which the climate sensitivity is changed through cloud radiative adjustment to results of simulations in which the climate sensitivity of CAM3 is changed using the perturbed physics approach. To verify that the cloud radiative adjustment method can be used safely to vary the model's climate sensitivity over the full range of uncertainty, we investigate the behavior of CAM3 for very low and very high values of climate sensitivity by comparing scaled patterns of changes for different values of climate sensitivity. Finally, we compare results of equilibrium simulations with CAM4 (CS = 3.1° C) and with two versions of CAM5 (CS = 4.2° C and CS = 5.1° C) and with versions of CAM3 with matching values of climate sensitivity obtained using the cloud radiative adjustment method.

2. Model and methodology

a. Models

The model used in this study is the NCAR CAM3 (Collins et al. 2004). This serves as the atmospheric component of the Community Climate System Model, version 3 (CCSM3) (Collins et al. 2006), and is coupled to

the Community Land Surface Model, version 3 (CLM3), described in Oleson et al. (2004). In fully coupled mode, the atmospheric model interfaces with a fully dynamic ocean model; however, for this project, CAM3 is coupled to a slab ocean model. This study uses CAM3 at $2^{\circ} \times 2.5^{\circ}$ resolution and at T21 spectral truncation, which corresponds to a roughly uniform $5.6^{\circ} \times 5.6^{\circ}$ Gaussian grid. Vertically, the model evaluates three-dimensional atmospheric variables on 26 levels, with the lowest levels in sigma coordinates and the uppermost levels in pure pressure coordinates. The standard version of this model has a climate sensitivity to a doubling of CO₂ concentrations of 2.6°C at T21 spectral truncation and of 2.2°C at $2^{\circ} \times 2.5^{\circ}$ resolution, which is consistent with Kiehl et al. (2006) who show that the climate sensitivity of CCSM3 varies with resolution.

The cloud radiative adjustment method is compared to the perturbed physics approach as well as to simulations with versions of the NCAR Community Model, CAM4 and CAM5 at $1.9^{\circ} \times 2.5^{\circ}$ resolution. Versions of the model at T21 spectral truncation with a higher and a lower climate sensitivity were obtained using the perturbed physics approach, by changing the critical relative humidity for cloud formation for high and low clouds. Recently released versions of the NCAR Community Model, CAM4 and CAM5, have a higher climate sensitivity than CAM3. The climate sensitivity of CAM4 is 3.1°C, while the climate sensitivity of the different versions of CAM5 ranges from 3.9° to 5.1°C (Gettelman et al. 2010). The physical parameterization suite used in CAM4 is rather similar to that used in CAM3, the major differences involving the parameterization of deep convection and momentum transport. In addition, the calculation of cloud fraction was modified in CAM4 and includes a "freeze drying" process in the lower troposphere that mainly affects the Arctic region (Neale et al. 2010a). On the other hand, CAM5 uses completely different parameterizations, the only major parameterization common to CAM4 and CAM5 being the deep convection (Neale et al. 2010b). Nevertheless, differences in climate sensitivity between CAM4 and CAM5 are almost exclusively due to differences in cloud feedback (Gettelman et al. 2012).

b. Methodology

Sanderson (2011) carried out a number of simulations with the $2^{\circ} \times 2.5^{\circ}$ version of CAM3.5 changing four parameters of the model. This study revealed that CAM3.5 is much less sensitive to parameter changes than some other climate models. As a result, the range of climate sensitivity to a doubling of CO₂ obtained by the perturbed physics approach is rather narrow, from 2.2° to 3.2°C, while the sensitivity of the unperturbed version is 2.4°C.

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TABLE 1. Climate sensitivity of CAM3 at T21 spectral truncation obtained by changing the values of critical relative humidity (RHmin) for high and low cloud formation. The boldface values correspond to the standard version of CAM3, while the italic values correspond to two versions of CAM3 used in this study.

RHmin for low clouds	RHmin for high clouds	Climate sensitivity	
0.90	0.80	2.60	
0.90	0.90	2.59	
0.90	0.70	2.59	
0.85	0.80	2.31	
0.95	0.80	2.69	
0.85	0.90	2.16	
0.95	0.70	2.74	
0.80	0.95	2.01	
0.975	0.65	2.86	

In this study, several simulations were performed with CAM3 at T21 spectral truncation using different values of the parameters affecting the formation of high and low clouds. Results of some of these simulations are shown in Table 1. Unfortunately even rather large changes in the model's parameters result in very small changes in the climate sensitivity of the model.

The sensitivity of the climate model to an external forcing, as noted previously, can also be varied by changing the strength of the cloud feedback. Namely, the cloud fraction used in the radiation calculations is adjusted as follows:

$$C^{\text{RAD}} = C^{\text{MODEL}}(1.0 \pm \kappa \Delta T_{\text{out}}), \qquad (1)$$

where C^{MODEL} and C^{RAD} are, respectively, the cloud fractions simulated by the model and used in the radiation calculations, ΔT_{srf} is the difference in the global mean daily mean surface air temperature from its value in a control climate simulation and is equal to the climate sensitivity of the model once the simulation has reached equilibrium, and κ is the cloud feedback parameter. The adjustment is applied, with different signs, to high (–) and low (+) clouds. Changing high and low clouds in opposite directions is related to the fact that the feedback associated with changes in cloud cover has different signs for high and low clouds. Therefore, using different signs in Eq. (1) depending on cloud heights minimizes the value of κ required to obtain a specific value of climate sensitivity (Sokolov 2006).

Figure 1 shows the equilibrium climate sensitivity as a function of κ for two resolutions of CAM3 [see also Table 2 for more details about the T21 spectral truncation simulations and Sokolov and Monier (2011) for the $2^{\circ} \times 2.5^{\circ}$ version]. This approach has a number of advantages compared to the perturbed physics approach.



FIG. 1. Climate sensitivity as a function of the cloud feedback parameter for CAM3 at $2^{\circ} \times 2.5^{\circ}$ resolution and at T21 spectral truncation.

First, it is more computationally efficient. Obtaining a value of climate sensitivity using the perturbed physics approach requires three climate simulations: one with prescribed sea surface temperature and sea ice distribution to calculate the implied ocean heat transport (Q flux), a control climate simulation with the slab ocean model and with fixed CO₂ concentrations, and finally a doubled-CO₂ simulation with the slab ocean model. In contrast, because the cloud radiative adjustment does not affect the control climate simulation, only one simulation is required if this approach is used. In addition, the cloud radiative adjustment method can produce versions of the model with a wide range of climate sensitivity. Simulations with the MIT Integrated Global System Model

TABLE 2. Climate sensitivity of CAM3 at T21 spectral truncation obtained by the cloud radiative adjustment method along with the corresponding cloud feedback parameter and cloud multiplier.

к	$\Delta T_{\rm srf}$	Multiplier for low clouds	Multiplier for high clouds
0.217 99	0.48	1.10	0.90
0.159 19	0.57	1.09	0.91
0.096 35	0.83	1.08	0.92
0.049 10	1.29	1.06	0.94
0.022 45	1.73	1.04	0.96
0.015 49	1.95	1.03	0.97
0.000 00	2.60	1.00	1.00
-0.003 64	2.86	0.99	1.01
-0.006 83	3.23	0.98	1.02
-0.014 32	4.17	0.94	1.06
-0.021 30	6.30	0.87	1.13
-0.024 55	8.61	0.79	1.21
-0.030 99	13.39	0.59	1.41

(IGSM), a fully coupled earth system model of intermediate complexity, showed that any given value of climate sensitivity can be obtained with a 0.1°C precision using a lookup table (like Table 2) with about 25 reference values.

According to simulations with a model of intermediate complexity, the cloud radiative adjustment method does affect interannual variability, but the impact on decadal variability is very small even in simulations with a mixed layer ocean model. Because the cloud adjustment is based on the change in global mean air temperature, it is unlikely to have a significant impact on regional variability.

Studying uncertainty in future climate change requires knowledge of probability distributions of climate parameters affecting the climate system response to changes in the external forcing. Under the perturbed physics approach, the probability distribution of climate sensitivity can be obtained by comparing results from present-day climate simulations for different model parameters with available observations. Because the cloud radiative adjustment method does not affect the control climate, a different method for estimating PDFs of climate parameters was developed by Forest et al. (2001). This method is based on the comparison of twentiethcentury climate simulated by the model for a wide range of climate parameters (climate sensitivity, rate of ocean heat uptake, and strength of aerosol forcing) with observed changes in surface and upper air temperature and deep ocean heat content. For each diagnostic, the likelihood that a given simulation is consistent with the observed changes, allowing for observational error and natural variability, is estimated using goodness-of-fit statistics from climate change detection methods. By combining the likelihood distributions estimated from each diagnostic using Bayes's theorem, a posterior probability distribution can be obtained (see Forest et al. 2008).

The probability distributions of climate parameters, together with probability distributions of anthropogenic emissions of different greenhouse gases and aerosols can be used to conduct probabilistic climate forecasts using efficient sampling techniques (Sokolov et al. 2009; Webster et al. 2011).

3. Validation of the cloud radiative adjustment method

a. Comparison to perturbed physics approach

The climate sensitivity of the standard version of CAM3 at T21 spectral truncation is 2.6° C. Two versions of CAM3 T21 with CS = 2.0° C and CS = 3.0° C were obtained through a perturbed physics approach (Table 1), using different values of critical relative humidity for high and low cloud formation. In this section we present

a comparison between simulations with these two versions of CAM3 and with two versions of CAM3 with similar values of climate sensitivity obtained using the cloud radiative adjustment method. In addition to doubled-CO₂ simulations, equilibrium simulations were carried out with a five-time increase in sulfate aerosol concentrations. The radiative forcing due to the increase in aerosol concentrations for the standard version of CAM3, -3.4 W m⁻², is similar in magnitude to the 3.6 W m⁻² forcing due to a doubling of CO₂ (Kiehl et al. 2006).

Changes in global mean annual mean surface air temperature and precipitation obtained in simulations with similar values of climate sensitivity are close, regardless of how the climate sensitivity was changed. Both methods show an overall good agreement in the equilibrium temperature, response time, and magnitude of the interannual variability. The use of the cloud radiative adjustment approach for different types of forcing (e.g., solar, black carbon) was previously tested in simulations with the MIT IGSM (Sokolov 2006), showing the method is suitable for other external forcing than CO_2 and sulfate aerosols. However, it should be noted that neither CAM3 nor the MIT IGSM take into account the indirect forcing associated with sulfate aerosols.

Figure 2 shows maps of changes in surface air temperature and total precipitation in response to a doubling of CO₂ concentrations and to a five-time increase in sulfate aerosol concentrations using both methods to change the climate sensitivity of CAM3. These simulations show a broad agreement in the general distribution of changes in surface air temperature between the two methods, with a distinct polar amplification and a stronger response over land. Nonetheless, there are some regional differences between the two methods. For example, the doubled-CO₂ simulation with low climate sensitivity based on the perturbed physics approach produces a smaller warming amplification in high latitudes in the Northern Hemisphere, but a larger warming over Antarctica compared to the cloud adjustment method. Meanwhile, the perturbed physics simulation with a high climate sensitivity displays a region of strong warming over the eastern part of Russia that is absent in the corresponding cloud adjustment simulation. The simulations with a five-time increase in sulfate aerosol concentrations also present regional differences between the two methods. In particular, the perturbed physics simulations display a stronger cooling than the cloud adjustment simulations in the polar regions, over eastern Europe and over the Great Lakes region in North America.

Both methods also agree generally well in both pattern and magnitude of precipitation changes, with the largest differences occurring over the western Pacific Ocean. One striking feature of the perturbed physics



FIG. 2. Changes in surface air temperature in response to (a) a doubling of CO_2 concentrations and (b) a five-time increase sulfate aerosol concentrations, and changes in total precipitation in response to (c) a doubling of CO_2 concentrations and (d) a five-time increase sulfate aerosol concentrations. Simulations are shown for a low climate sensitivity (CS = 2.0°C) and a high climate sensitivity (CS = 3.0°C). Simulations based on the cloud radiative adjustment method are denoted as CLDADJ, while simulations based on the perturbed physics approach are denoted as PP.

approach is that the simulation with the lower climate sensitivity displays larger changes in precipitation in the tropics than the simulation with the higher climate sensitivity. The two perturbed physics simulations also show regional changes of opposite signs like, for example, over most of the Maritime Continent. This is the result of modifying parameters that can impact cloud formation differently between high and low clouds and therefore lead to different regional responses. With the perturbed physics approach, it is possible to obtain the same climate sensitivity for two sets of model parameters, but with different regional patterns of change. As such, the perturbed physics approach provides a method to investigate the uncertainty in regional patterns as well as in the global response to changes in external forcing.

Figure 3 shows the changes in the vertical structure of zonal mean air temperature and relative humidity associated with a doubling of CO_2 concentrations and

a five-time increase in sulfate aerosol concentrations. Once again, there is good agreement between the perturbed physics approach and the cloud radiative adjustment method albeit some differences in the magnitude of the response. Both doubled-CO₂ simulations show a fairly symmetric response in the zonal mean air temperature, with the largest changes in the polar region lower troposphere and in the tropical upper troposphere. Meanwhile the response to increasing sulfate aerosol concentrations is much stronger in the Northern Hemisphere for both methods of changing the climate sensitivity of the model. The largest cooling is located in the midlatitudes and polar region over most of the troposphere and in the upper troposphere over the tropics and over the Northern Hemisphere subtropics. However, the perturbed physics simulations display a slightly stronger warming in the tropical upper-troposphere as a response to a doubling of CO_2 , as well as a stronger cooling in the



FIG. 3. As in Fig. 2, but for latitude-height cross sections of air temperature and relative humidity.

Northern Hemisphere midlatitudes and polar region over most the troposphere when sulfate aerosol concentrations are increased.

Similarly, there is a very good agreement between both methods in the vertical structure of changes in the zonal mean moisture field. While the magnitude of the changes vary between the two methods in specific regions, the latitudinal location of the largest changes, the sign and the vertical profile of the changes all match very well. This further demonstrates that both methods show consistent behavior in the equilibrium response to an external forcing, whether it is a doubling of CO_2 concentrations or an increase in sulfate aerosol concentrations.

These results show that the equilibrium climate response to both a positive and a negative forcing is not very sensitive to how the climate sensitivity of CAM3 is changed. It should be noted that the similarity between the patterns of change obtained under the two different methods is likely due to the use of physical parameters directly affecting cloud formation in the perturbed physics approach. It might not be the case if different physical parameters were used.

As was shown in a number of studies (e.g., Raper et al. 2002), the transient climate response to a gradually changing forcing is determined by the effective climate sensitivity, which can be changing in time (Murphy 1995). To simulate the transient climate response, CAM3 is coupled to a temperature-anomaly diffusing ocean model (Sokolov and Stone 1998; Hansen et al. 2002). The anomaly diffusing ocean model was shown to simulate well the mixing of heat into the deep ocean (Sokolov and Stone 1998; Sokolov et al. 2003). Figure 4 shows the transient surface warming in simulations with a $1\% \text{ yr}^{-1}$ increase in atmospheric CO₂ concentrations along with climate simulations for the years 1870 to 2100 using observed forcing (different greenhouse gases, solar, volcanic aerosols, and others) through year 2000 and forcing based on business as usual (BAU) emissions scenario for the twenty-first



FIG. 4. Changes in surface air temperature for (a) a 1% yr⁻¹ increase in CO₂ concentrations and (b) a business as usual (BAU) emissions scenario in simulations with CAM3 at T21 spectral truncation coupled to an anomaly diffusing ocean model. The BAU simulation include two sets of initial conditions (inic) but are limited to one climate sensitivity (CS = 3.0° C). Simulations based on the cloud radiative adjustment method are denoted as CLDADJ, while simulations based on the perturbed physics approach are denoted as PP.

century. The 1% yr⁻¹ increase simulations show very good agreement between the perturbed physics approach and the cloud adjustment method for both low and high climate sensitivities. The same is true for the climate response to a gradual increase in the sulfate aerosol loading (not shown). Overall, the changes in surface air temperature of the BAU simulations with the cloud radiative adjustment method track very well the simulations based on the perturbed physics approach. During the twentieth century, the year-to-year changes associated with natural interannual variability and volcanic eruptions are in very good agreement between the two methods. Furthermore, the warming trends over the twenty-first century are an excellent match.

In general, the equilibrium and the transient climate responses produced by CAM3 based on the perturbed physics approach and the cloud radiative adjustment method agree well with each other. The perturbed physics approach can produce large differences in the regional response for two climate sensitivities that are not very different (CS = 2.0° C and CS = 3.0° C), in particular for precipitation. This is due to the large changes in the model parameters that are required to obtain values of climate sensitivity that are not very different (within a 1.0°C range). On the other hand, the cloud radiative adjustment method produces patterns of change that appear similar, but with different magnitudes for the two different climate sensitivities. While the cloud adjustment method seems to provide a stable method to obtain large changes in the climate sensitivity of the model, this needs to be confirmed by investigating the behavior of the model with a much lower and a much higher climate sensitivity.

As was noted previously, the range of climate sensitivity of most climate models, with the exception of the Hadley Centre model (Stainforth et al. 2005), obtained using the perturbed physics approach is narrower than the range suggested by twentieth-century climate change. The latter includes values from 1.0° to about 6.0°C (e.g., Forest et al. 2008; Knutti et al. 2003). Obtaining such climate sensitivities using the cloud radiative adjustment method requires changing clouds used in the radiation calculations by as much as 15% compared to the clouds simulated by the climate model. To check that such a significant cloud adjustment does not lead to a physically unrealistic climate system response to an external forcing, we compare the changes simulated by versions of CAM3 with a rather low and high climate sensitivity, namely, $CS = 1.3^{\circ}C$ and $CS = 6.2^{\circ}C$, with the changes simulated by the standard version of CAM3.

Figure 5 displays maps of changes in surface air temperature, total precipitation, and turbulent heat fluxes scaled by the respective value of climate sensitivity. The normalized changes in surface temperature show a good agreement in the patterns of change, but with differences in magnitude in various regions. In particular, it shows that the version of CAM3 with the lowest climate sensitivity produces the strongest polar amplification relative to its global response. As was noted by Sokolov (2006), the impact of the cloud adjustment on the strength of the cloud feedback is somewhat smaller in simulations with larger sea ice and snow extent. This would suggest that changes in the cloud feedback in high latitudes will be smaller than in the regions with relatively low surface albedo. As a result, the strength of the cloud feedback will be larger (smaller) than the

(a) Changes in Surface Air Temperature



(b) Changes in Total Precipitation



(c) Changes in Surface Latent Heat Flux



(d) Changes in Surface Sensible Heat Flux



FIG. 5. Normalized changes in (a) surface air temperature, (b) total precipitation, (c) surface latent heat flux, and (d) surface sensible heat flux in response to a doubling of CO_2 concentrations for low, standard, and high climate sensitivity obtained using the cloud radiative adjustment method. The changes are normalized by the respective value of climate sensitivity.

global mean in simulations with a low (high) climate sensitivity.

The normalized changes in precipitation also show somewhat different regional patterns of change. In particular, the lowest climate sensitivity version of CAM3 exhibits a decrease in precipitation over Malaysia and the Philippines, over the north of Peru, and from Côte d'Ivoire to Nigeria, while the highest climate sensitivity

TABLE 3. Global mean changes in surface net radiative flux (SRFRAD), surface net longwave radiation (FLNS), surface net shortwave radiation (FLNS), surface latent heat flux (LHFLX), and surface sensible heat flux (SHFLX; W m⁻²) in response to a doubling of CO₂ concentrations with CAM3 at T21 spectral truncation for three values of climate sensitivity (CS = 1.3° C, CS = 2.6° C, and CS = 6.3° C) obtained through cloud radiative adjustment.

CS	1.25	2.56	6.35
SRFRAD	1.55	2.72	6.80
FLNS	2.44	3.44	4.29
FSNS	-0.89	-0.72	2.51
LHFLX	2.14	4.21	10.30
SHFLX	-0.58	-1.46	-3.41

version of CAM3 shows the opposite. This underlines the existence of different regional patterns of change obtained with the cloud radiative adjustment method.

The magnitudes of maxima and minima of simulated changes in latent and sensible heat fluxes are noticeably larger (relative to the global mean change) in simulation with a low climate sensitivity. This most likely is a result of smaller signal-to-noise ratio for smaller climate sensitivity and is, to a different extent, the case for changes in all variables.

Changes in net radiation at the top of the model and at the surface scale with the model's climate sensitivity, both globally and regionally (see Table 3 and Fig. 6). In contrast changes in shortwave and longwave radiation at the surface differ significantly as a function of the climate sensitivity, which is consistent with the fact that high and low clouds have different impacts on radiative fluxes. For example, significant decreases in low clouds over high-latitude regions in the simulation with CS =6.3°C lead to an increase in incoming shortwave radiation and a decrease in incoming longwave radiation. In the other two simulations, the low clouds show small increases over the whole globe, which causes a decrease in shortwave radiation. Such changes in the components of the surface radiation are consistent with changes simulated by different GCMs (see Fig. 6 in Sokolov 2006) and with results for different versions of CAM shown in section 3b below.

Despite these regional differences, the changes simulated by versions of CAM3 with rather low and high values of climate sensitivity agree well with the changes simulated by the standard version of CAM3. Figure 7 displays latitude–height cross sections of changes in zonal mean air temperature and zonal mean relative humidity also scaled by the respective value of climate sensitivity. Similarly to the maps of surface changes, the zonal mean cross sections show that the largest differences are the magnitudes of the changes relative to the value of the climate sensitivity. The structure of the changes are quite similar in all three simulations even though there can be small differences. For example, the largest decrease in moisture in the tropical upper troposphere occurs north of the equator in the standard and highest climate sensitivity versions of CAM3, but south of the equator in the lowest climate sensitivity version. This analysis suggests that CAM3 versions with values of climate sensitivity noticeably different from that of the standard version, in spite of significant changes in the cloud cover used in the radiation calculations, simulate physically plausible changes in climate. At the same time, it demonstrates that the cloud radiative adjustment method can produce different regional patterns of change like the perturbed physics approach.

The previous comparison does not indicate that such extreme values of climate sensitivity are plausible (or not plausible), but simply shows that the cloud radiative adjustment method can be safely used to obtain values of climate sensitivity noticeably different from the climate sensitivity of the standard version of the climate model.

b. Comparison to CAM4 and CAM5 simulations

In this section, we compare results of equilibrium doubled-CO₂ simulations with CAM4 (CS = 3.1° C) and two versions of CAM5 (CS = 4.2° C and CS = 5.1° C) with results of simulations with versions of CAM3 with matching climate sensitivities obtained using the cloud radiative adjustment method. The data from simulations with CAM4 and CAM5 were provided by Dr. A. Gettelman (2011, personal communication). To minimize the differences in simulated climate change associated with differences in the horizontal resolution of CAM, the simulations with CAM3 were carried out at a resolution of $2^{\circ} \times 2.5^{\circ}$, similar to that of CAM4 and CAM5. The climate sensitivity of the standard $2^{\circ} \times 2.5^{\circ}$ version of CAM3 is 2.2°C. Simulations with CAM3 with climate sensitivities of 3.1°, 4.2°, and 5.1°C correspond to about 5%, 9%, and 14% changes in cloud cover in the radiation calculations, respectively. All results shown in this section are differences between 40-yr means from doubled-CO₂ and control simulations.

Since the cloud radiative adjustment method revolves around artificially changing the cloud feedback in the radiation calculations, we first compare changes in low and high clouds in simulations with the different versions of CAM (Fig. 8), where differences for clouds used in the radiation calculations are shown for CAM3. Figure 8 shows that the physical changes in low clouds taking place in the CAM4 and CAM5 simulations are overall larger than the artificial changes in CAM3. There are noticeable differences in the changes over high latitudes (especially for the Northern Hemisphere) between all

(a) Changes in Surface Net Longwave Radiation



(b) Changes in Surface Net Shortwave Radiation



-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7

(c) Changes in Surface Net Radiative Flux



(d) Changes in Top of Model Net Radiative Flux



FIG. 6. As in Fig. 5, but for (a) surface net radiative flux, (b) top-of-model net radiative flux, (c) surface net longwave radiation, and (d) surface net shortwave radiation.

versions of CAM. As can be expected, the magnitude of changes increases with increasing climate sensitivity in simulations with CAM3. There is no such dependency in simulations with CAM4 and CAM5; in particular, the

simulation with the low climate sensitivity version of CAM5 (CS = 4.2° C) produces larger increases in low clouds over the Northern Hemisphere polar region than either CAM4 or the high climate sensitivity version of

(a) Changes in Zonal-Mean Air Temperature



FIG. 7. Latitude–height cross sections of normalized changes in (a) air temperature and (b) relative humidity in response to a doubling of CO_2 concentrations for low, standard, and high climate sensitivity obtained using the cloud radiative adjustment method. The changes are normalized by the respective value of climate sensitivity.

CAM5. Meanwhile, CAM3 produces a decrease in low clouds over this region in all simulations. Similarly, there is a clear disagreement over the coast of Antarctica between CAM4/CAM5 simulations that show an increase in low clouds and CAM3 simulations that systematically produce a decrease in low clouds. These differences can be largely explained by fundamental differences in the representation of low clouds between CAM3 and CAM4/ CAM5, such as the representation of a freeze-dry process in the lower troposphere that largely affects Arctic clouds (Neale et al. 2010a). The agreement over nonpolar regions is much better, especially between simulations with a high climate sensitivity. Figure 8 also shows that changes in high clouds agree well overall, with the largest differences taking place over the tropics, where CAM3 produces a decrease in high clouds that is much larger than in CAM4 and CAM5. This can be explained by the change in deep convection parameterization from CAM3 to CAM4. Figure 8 indicates that the changes in high and low clouds required by the cloud radiative adjustment scheme to obtain different values of climate sensitivity are overall consistent with the changes simulated by versions of CAM in which the differences in climate sensitivity are caused by the use of different physical parameterizations and/or different models parameters.

Figure 9 shows the changes in surface air temperature and total precipitation for all CAM3, CAM4, and CAM5 simulations. There is good agreement in the magnitude and spatial patterns of changes in temperature over most regions, with the largest discrepancies taking place over the polar regions. In particular, the Northern Hemisphere polar amplification is much stronger in the simulation with the low climate sensitivity version of CAM5 than in the corresponding CAM3 simulation. As such, there is an apparent inconsistency between the changes in clouds and surface air temperature. As was already mentioned, the low climate sensitivity version of CAM5 simulates an increase in low cloud cover over the Northern Hemisphere high latitudes, while the corresponding version of CAM3 simulates a small decrease. Because of the negative cloud feedback associated with increasing low clouds, this would imply a smaller surface warming over this region in simulations with CAM5. However, Fig. 9 shows the opposite. This apparent discrepancy is most likely associated with the use of a different sea ice model in CAM3 and CAM5. Indeed, CAM5 simulations produce a larger decrease in sea ice cover in the Northern Hemisphere. As a result, the amount of solar radiation absorbed at the surface increases despite a decrease in incoming solar radiation. The differences in the strength

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(a) Changes in Low Clouds



-24 -20 -16 -12 -8 -4 0 4 8 12 16 20 24

FIG. 8. Changes in (a) low clouds and (b) high clouds in response to a doubling of CO_2 concentrations with CAM4 (CS = 3.1°C) and CAM5 (CS = 4.2°C and CS = 5.1°C) and with versions of CAM3 with matching climate sensitivities. Clouds used in the radiation calculations are shown for CAM3.

of the cloud feedback associated with the varying cloud parameterizations in the three versions of CAM are also likely to play a part in this apparent discrepancy. As for the changes in total precipitation, they are almost exclusively the result of changes in convective precipitation while changes in large-scale precipitation are similar for all versions of CAM (Sokolov and Monier 2011). Such differences are consistent with the differences in convection parameterizations between the various versions of CAM. Changes in surface and in top-of-model net radiative fluxes are shown in Fig. 10. The largest differences in changes in surface net radiative flux between CAM3 and CAM4/CAM5 take place over the Northern Hemisphere polar region, which is not surprising considering the previous results. These differences are primarily due to disparities in changes in absorbed solar radiation, while changes in the net longwave flux (Fig. 11) are consistent between simulations with similar values of climate sensitivity. Elsewhere, the changes in surface net radiation

(a) Changes in Surface Air Temperature



FIG. 9. Changes in (a) surface air temperature and (b) total precipitation in response to a doubling of CO_2 concentrations with CAM4 (CS = 3.1°C) and CAM5 (CS = 4.2°C and CS = 5.1°C) and with versions of CAM3 with matching climate sensitivities.

flux match well, with a noticeably better agreement between CAM3 and CAM4 than between CAM3 and CAM5. The changes in top-of-model net radiative flux shows large discrepancies over the tropics, which are due to differences in high clouds resulting from varying deep convection parameterizations between CAM3 and CAM4/CAM5. The partitioning between changes in surface latent heat flux and sensible heat flux also presents differences between the three versions of CAM (Fig. 12). For example, CAM4/CAM5 simulations show a larger increase in surface latent heat flux in the polar region over the ocean, while CAM3 simulations exhibit a larger increase in evaporation over land. These discrepancies can be attributed to the differences in low clouds and sea ice mentioned previously and to the use of different land surface models, respectively. CAM4/CAM5 simulations also produce a larger increase in sensible heat flux in the Northern Hemisphere polar region and near the coast of Antarctica. Meanwhile, the CAM3 simulations display strong decreases over land, in particular over Africa, which are not present in the CAM4/CAM5 simulations. These differences likely have the same origin

6580

(a) Changes in Surface Net Radiative Flux





FIG. 10. As in Fig. 9, but for (a) surface net radiative flux and (b) top-of-model net radiative flux.

as the disparities in changes in surface latent heat flux. It is worth noting that the large biases in evaporation and sensible heat flux over land are present in simulations with the standard version of CAM3, further demonstrating that they are not caused by the cloud radiative adjustment method.

Overall, this analysis demonstrates that the largest differences between the CAM3, CAM4, and CAM5 simulations presented in this paper are associated with changes in sea ice model, land surface model, or parameterization schemes, and not with the implementation of the cloud radiative adjustment method.

4. Discussion and conclusions

In this paper we describe a method for changing the climate sensitivity of atmospheric models based on a cloud radiative adjustment scheme, where the cloud cover used in the radiation calculations is artificially changed. This approach was previously tested in simulations with the MIT Integrated Global System Model (IGSM), a fully coupled earth system model of intermediate complexity. Compared to the traditional perturbed physics approach, this method is more computationally efficient and produces a wider range of climate sensitivity. In addition,

(a) Changes in Surface Net Longwave Radiation



-30 -24 -18 -12 -6 0 6 12 18 24 30 W/m²

CAM5 (CS=4.2°C)

FIG. 11. As in Fig. 9, but for (a) surface net longwave radiation and (b) surface net shortwave radiation.

the cloud radiative adjustment method can produce any value of climate sensitivity within the range of uncertainty, thus allowing Monte Carlo–type probabilistic climate forecasts to be conducted where values of uncertain parameters not only cover the whole uncertainty range, but cover it homogeneously. The results show that the range of climate sensitivity suggested by observed twentieth-century climate change requires a cloud adjustment of the order of 10%–15%. However, the associated magnitude of cloud cover changes used in the radiation calculations is close to the physical changes in simulations with CAM4 and CAM5 with matching climate sensitivity. As a result,

CAM4 (CS=3.1°C)

the cloud radiative adjustment method does not involve physically unrealistic changes in cloud cover.

CAM5 (CS=5.1°C)

In this study, simulations with versions of CAM3 with different climate sensitivity obtained by the cloud radiative adjustment method are compared to simulations with various versions of CAM (CAM3, CAM4, and CAM5) where the climate sensitivity is changed by the perturbed physics approach and/or by different parameterizations of atmospheric processes. The results indicate that the cloud radiative adjustment method does not cause physically unrealistic behavior of the model's response to an external forcing, such as doubling CO₂

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(a) Changes in Surface Latent Heat Flux



FIG. 12. As in Fig. 9, but for (a) surface latent heat flux and (b) surface sensible heat flux.

concentrations or increasing sulfate aerosol concentrations. Overall, the equilibrium and the transient climate responses produced by CAM3 with the cloud radiative adjustment method agree well with the other versions of CAM. The major disparities are associated with differences in sea ice model, land surface model, and the use of different parameterization suites, such as different deep convection and cloud schemes, and not with the implementation of the cloud radiative adjustment scheme.

Versions of CAM3 with different values of climate sensitivity obtained using the cloud radiative adjustment method produce different regional changes. However, unlike the perturbed physics approach, the cloud radiative adjustment method can only produce one version of the model with a specific climate sensitivity, and thus with only one specific regional pattern of change. With the perturbed physics approach, it is possible to obtain versions of a model with the same climate sensitivity for two sets of model parameters. These versions can therefore produce very different regional patterns of change while having the same global response. For this reason, a limitation of the cloud radiative adjustment approach is that it cannot cover the full uncertainty in regional patterns of climate change.

Uncertainty in regional changes for some variables, such as temperature or precipitation, can be estimated using a pattern scaling approach and the distribution of climate sensitivity can be obtained from simulations with a climate model of intermediate complexity. However, as shown previously, regional and global changes for some variables do not scale with the value of climate sensitivity. In addition, simulations using an intermediate complexity model with different combinations of climate parameters (climate sensitivity, rate of ocean heat uptake, and strength of aerosol forcing), which produce similar changes in global mean climate, can simulate rather different zonal distributions. Using CAM3 with the cloud radiative adjustment method coupled to an ocean model can allow the study of the impact of uncertainty in climate sensitivity and oceanic heat uptake on the uncertainty in regional climate changes including regional patterns of atmospheric circulation, which cannot be done using a pattern scaling approach.

Overall, the results presented in this study show that the cloud radiative adjustment scheme is an efficient method to modify the climate sensitivity of an atmospheric model. This method can be used to estimate uncertainty in parameters of the climate system that affect its response to different forcing. It can also be used to perform probabilistic forecasts of future climate change.

Acknowledgments. We thank Dr. Andrew Gettelman for his comments and for providing data from simulations with different versions of CAM. The Joint Program on the Science and Policy of Global Change is funded by a number of federal agencies and a consortium of 40 industrial and foundation sponsors. (For the complete list see http://globalchange.mit.edu/sponsors/all.)

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