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Implementation of a Cloud Radiative Adjustment Method to Change the Climate Sensitivity of CAM3

Andrei Sokolov and Erwan Monier

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Implementation of a Cloud Radiative Adjustment Method to Change the Climate Sensitivity of CAM3

Andrei Sokolov*† and Erwan Monier*

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, we 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 a 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 20*th *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 which 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.*

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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 of each uncertain input controlling human emissions and the climate response (Reilly *et al.*, 2001; Forest *et al.*, 2001, 2002, 2006, 2008; Webster *et al.*, 2008). Then probabilistic climate projections are performed based on these probability distribution functions (Sokolov *et al.*, 2009, 2010; 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 (AOGCMs) using a

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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 20^{th} 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, 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, respectively CS=2.0°C and CS=4.0°C.

The algorithm for changing the cloud feedback was implemented in the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3). In this paper, we 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 CAM is changed using the perturbed physics approach. We also investigate the behavior of CAM3 for very low and very high values of climate sensitivity in order to verify that the cloud radiative adjustment method can be used safely and systematically to vary the model's climate sensitivity over the full range of uncertainty. Finally, we present 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

2.1 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°x2.5° resolution and at T21 spectral truncation, which corresponds to a roughly uniform 5.6°x5.6° 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 CO_2 concentrations of 2.6°C at T21 spectral truncation and of 2.2°C at 2°x2.5° 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°x2.5° resolution. Versions of the model at T21 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 are ranging from 3.9°C to 5.1°C (Gettelman *et al.*, 2011b). 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 affects mainly the Arctic region (Neale *et al.*, 2010b). 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.*, 2010a). Nevertheless, differences in climate sensitivity between CAM4 and CAM5 are almost exclusively due to differences in cloud feedback (Gettelman *et al.*, 2011a).

2.2 Methodology

Sanderson (2011) carried out a number of simulations with the 2°x2.5° 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 results, the range of climate sensitivity to a doubling of CO_2 obtained by the perturbed physics approach is rather narrow, from 2.16°C to 3.24°C, while the sensitivity of the unperturbed version is 2.43°C (**Figure 1**).

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:

$$C^{RAD} = C^{MODEL}\,(1.0 \pm \kappa \triangle T_{srf}) \qquad (1)$$

where C^{MODEL} and C^{RAD} are, respectively, the cloud fractions simulated by the model and used in the radiation calculations, $\triangle T_{srf}$ is the global-mean surface air temperature difference from its value in a control climate simulation and is equal to the climate sensitivity of the model once the

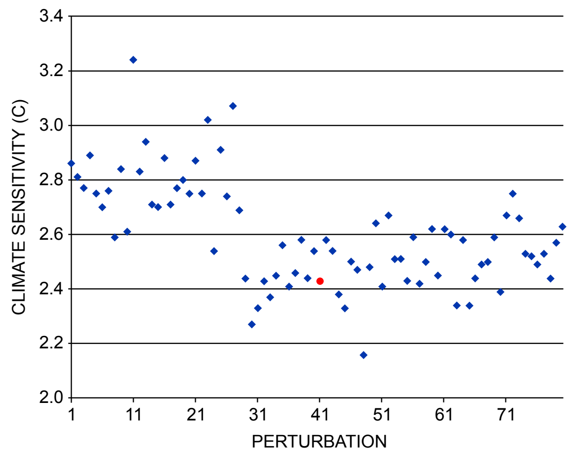

Figure 1. Climate sensitivity of CAM3.5 at 2°x2.5° resolution obtained by changing four parameters of the model. The red dot indicates the climate sensitivity of the unperturbed version of the model.

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 **Equation 1** depending on cloud heights minimizes the value of κ required to obtain a specific value of climate sensitivity (Sokolov, 2006).

Figure 2 shows the equilibrium climate sensitivity as a function of κ for two resolutions of CAM3 (see also **Table 2** and **Table 3**). This approach has a number of advantages compared to the perturbed physics approach. 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

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 values in red correspond to the standard version of CAM3, while the values in blue corresponds 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

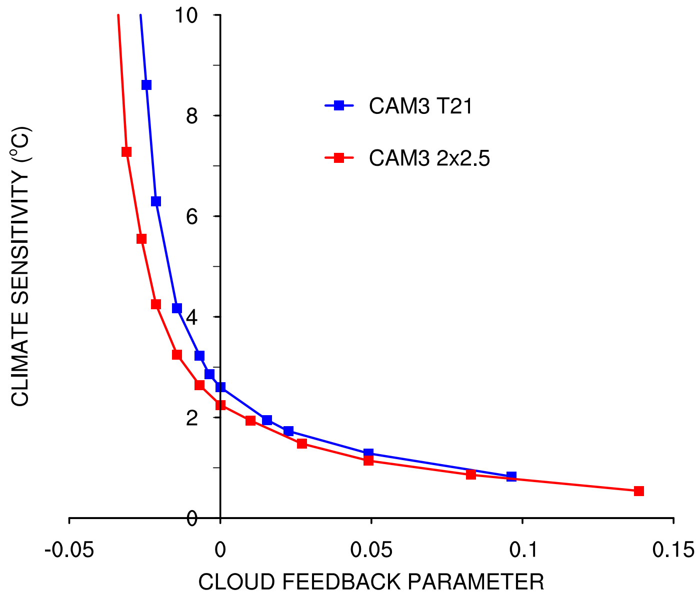

Figure 2. Climate sensitivity as a function of the cloud feedback parameter for CAM3 at 2°x2.5° resolution and at T21 spectral truncation.

CO_2 concentrations; and finally a doubled-CO_2 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 (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 (Table 2 and Table 3) with about 25 reference values.

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.

κ	$\triangle$**Tsrf**	**Multiplier for low clouds**	**Multiplier for high clouds**
0.2180	0.48	1.10	0.90
0.1592	0.57	1.09	0.91
0.0964	0.83	1.08	0.92
0.0491	1.29	1.06	0.94
0.0225	1.73	1.04	0.96
0.0155	1.95	1.03	0.97
0.0000	2.60	1.00	1.00
−0.0036	2.86	0.99	1.01
−0.0068	3.23	0.98	1.02
−0.0143	4.17	0.94	1.06
−0.0213	6.30	0.87	1.13
−0.0246	8.61	0.79	1.21
−0.0310	13.39	0.59	1.41

Table 3. Same as Table 2 but CAM3 at 2°x2.5° resolution.

κ	$\triangle$Tsrf	Multiplier for low clouds	Multiplier for high clouds
0.1386	0.58	1.08	0.92
0.0830	0.86	1.07	0.93
0.0491	1.16	1.06	0.94
0.0270	1.46	1.04	0.96
0.0100	1.84	1.02	0.98
0.0000	2.15	1.00	1.00
−0.0068	2.59	0.98	1.02
−0.0143	3.22	0.95	1.05
−0.0213	4.06	0.91	1.09
−0.0261	5.18	0.86	1.14
−0.0310	6.84	0.79	1.21
−0.0374	11.31	0.58	1.42

Therefore, this method allows Monte Carlo type probabilistic climate forecasts to be conducted using efficient sampling techniques (e.g. Latin hypercube sampling) where values of uncertain parameters not only cover the whole uncertainty range but cover it homogeneously (Sokolov *et al.*, 2009).

3. VALIDATION OF THE CLOUD RADIATIVE ADJUSTMENT METHOD

3.1 Comparison to Perturbed Physics Approach

The climate sensitivity of the standard version of CAM3 at T21 resolution 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-CO_2 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 CO_2 (Kiehl *et al.*, 2006).

Changes in global mean annual mean surface air temperature (**Figure 3**) and precipitation (not shown) 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

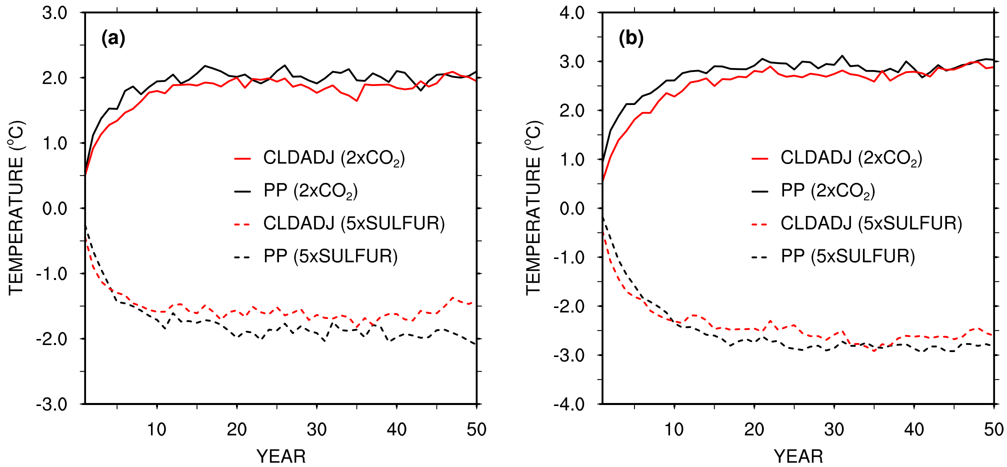

Figure 3. Changes in Surface Air Temperature in simulations with a doubling of CO_2 (2xCO_2) and a five-time increase in sulfate aerosol concentrations (5xSULFUR) for **(a)** low climate sensitivity (CS=2.0°C) and **(b)** high climate sensitivity (CS=3.0°C). Simulations based on the cloud radiative adjustment method are denoted as CLDADJ while simulations based on the perturbed physics approach are denoted as PP.

aerosols.

Figure 4 shows maps of changes in surface air temperature in response to a doubling of CO_2 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-CO_2 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

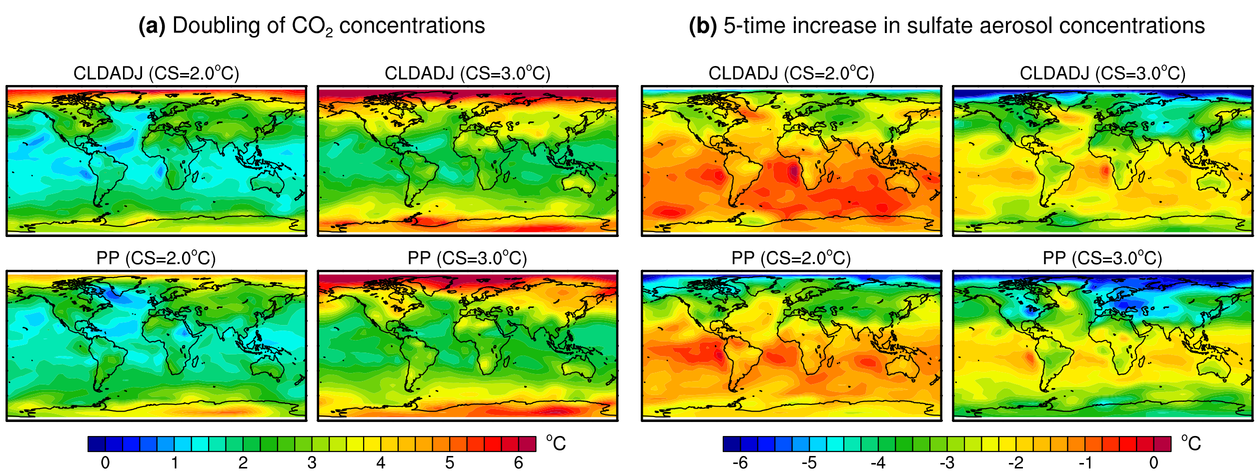

Figure 4. Changes in Surface Air Temperature in response to **(a)** a doubling of CO_2 concentrations and **(b)** a five-time increase in sulfate aerosol concentrations for low climate sensitivity (CS=2.0°C) and high climate sensitivity (CS=3.0°C). Simulations based on the cloud radiative adjustment method are denoted as CLDADJ while simulations based on the perturbed physics approach are denoted as PP.

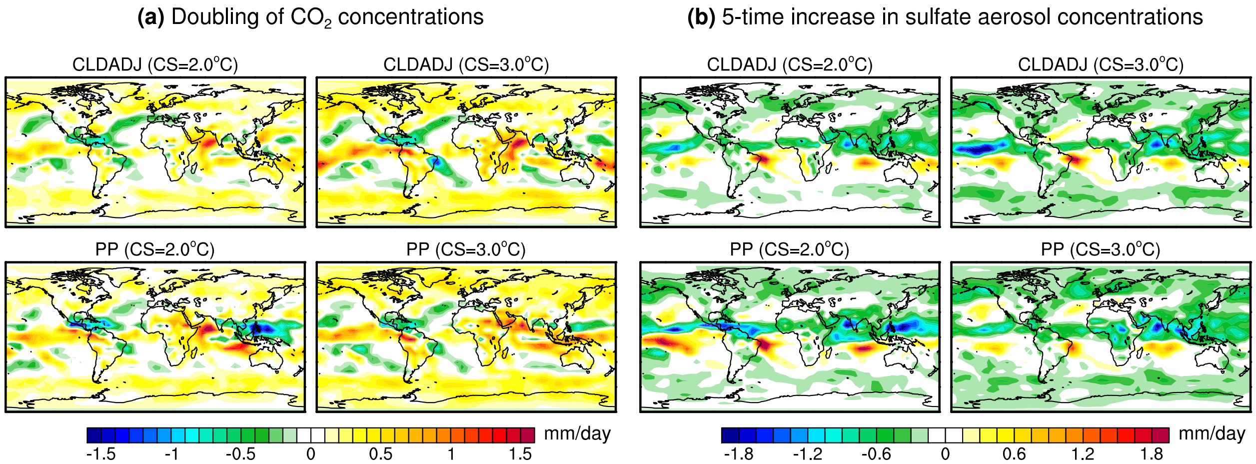

Figure 5. Same as Figure 4 but for Total Precipitation.

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.

Differences in precipitation changes are shown in **Figure 5**. Both methods 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 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 6 shows the changes in the vertical structure of zonal-mean air temperature 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-CO_2 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

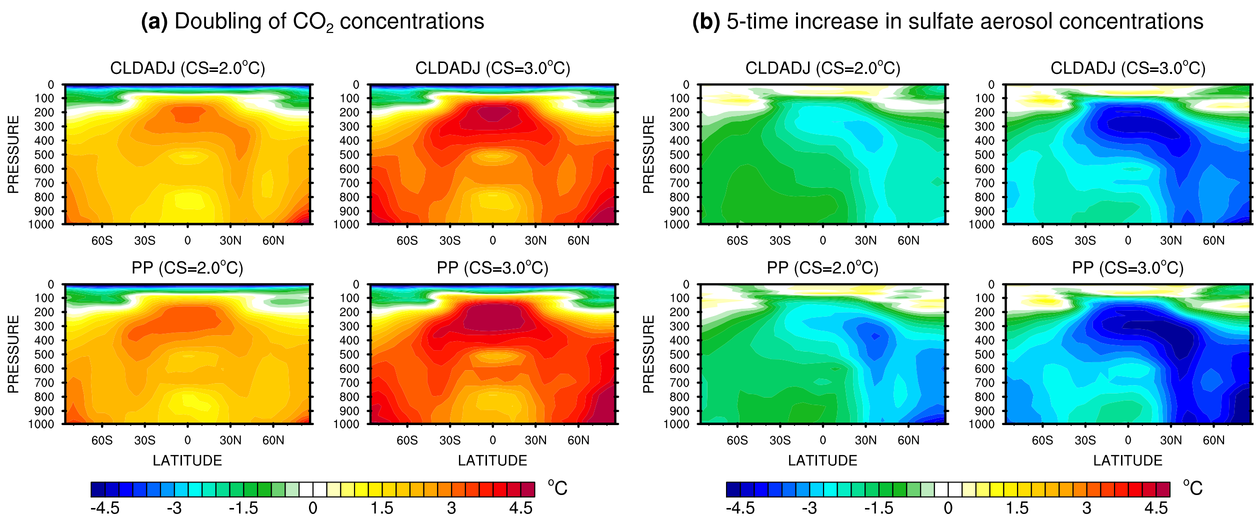

Figure 6. Same as Figure 4 but for Zonal-Mean Air Temperature.

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 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 (**Figure 7**). 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,

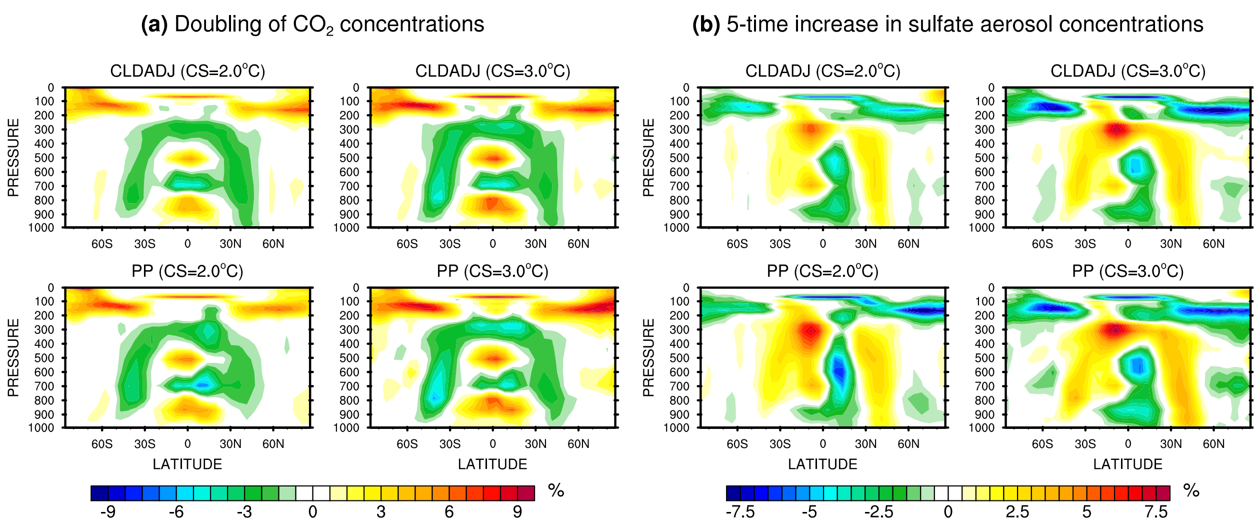

Figure 7. Same as Figure 4 but for Zonal-Mean Relative Humidity.

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. 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 8** shows the transient surface warming in simulations with a 1% per year increase in atmospheric CO_2 concentrations along with climate simulations for 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 21st century. The 1% per year 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 20th 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 21st 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

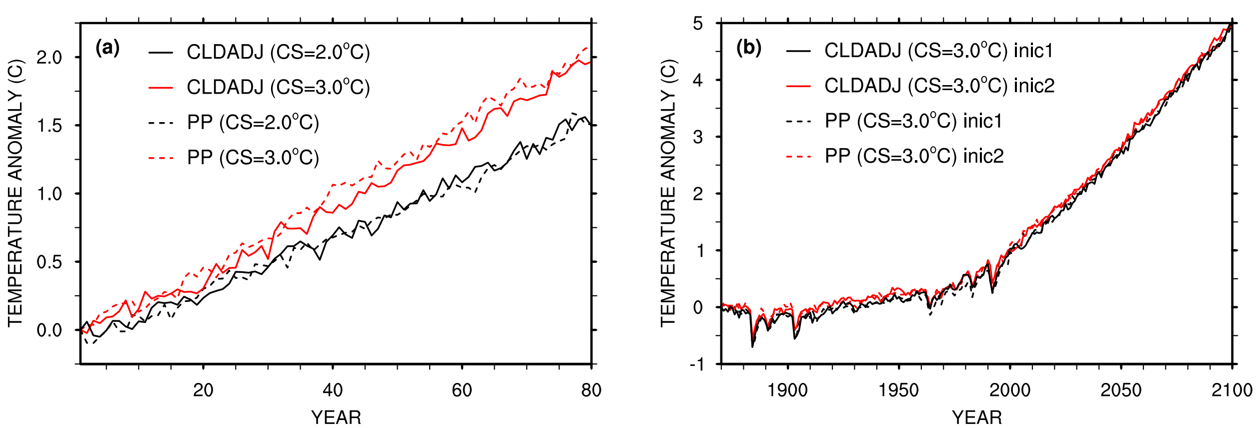

Figure 8. Changes in Surface Air Temperature for **(a)** a 1% per year increase in CO_2 concentrations and **(b)** a "Business As Usual" (BAU) emissions scenario in simulations with CAM3 at T21 spectral truncation coupled to an anomaly diffusing ocean model. The BAU simulation include two sets of initial 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.

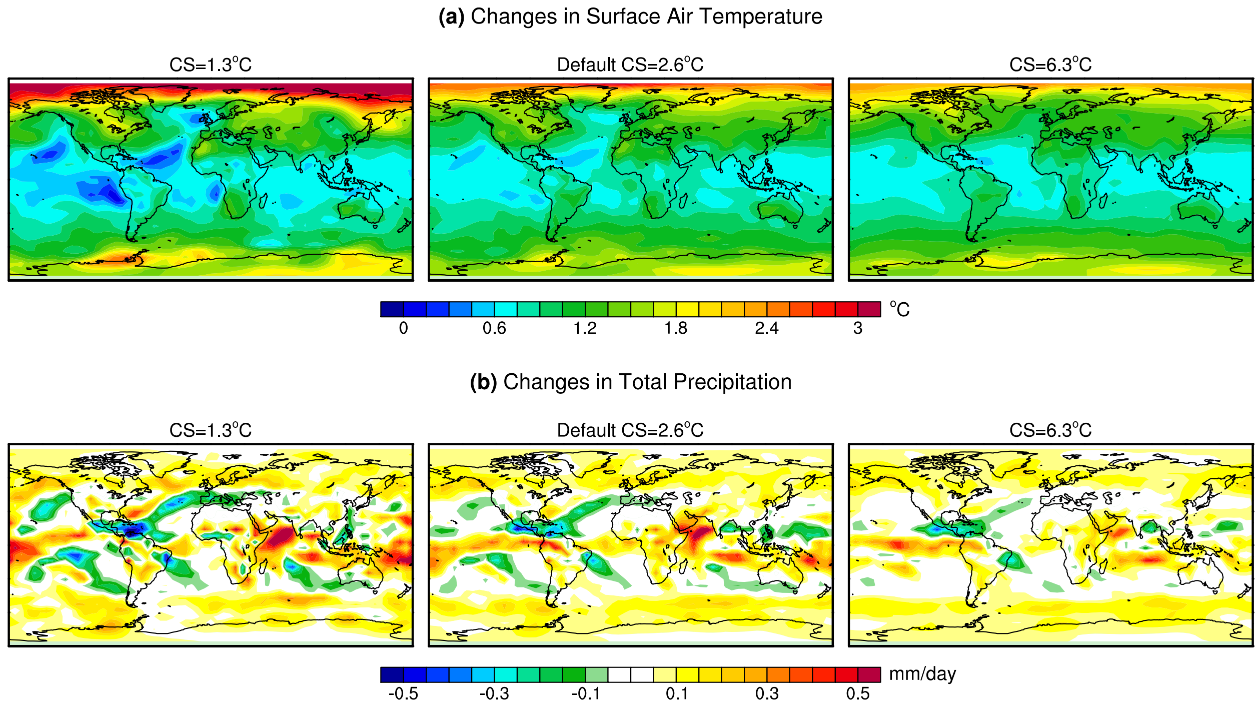

Figure 9. Normalized changes in **(a)** Surface Air Temperature and **(b)** Total Precipitation in response to a doubling of CO_2 concentrations for low, standard and high climate sensitivity obtained using the cloud radiative adjustment method. The changes are normalized by the respective climate sensitivity.

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, including CAM3, obtained using the perturbed physics approach is narrower than the range suggested by 20^{th} century climate change. The latter includes values from 1.0°C 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, we compare the changes simulated by versions of CAM3 with a rather low and high climate sensitivity, namely CS=1.3°C and CS=6.2°C, with the changes simulated by the standard version of CAM3.

Figure 9 displays maps of changes in surface air temperature and total precipitation 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

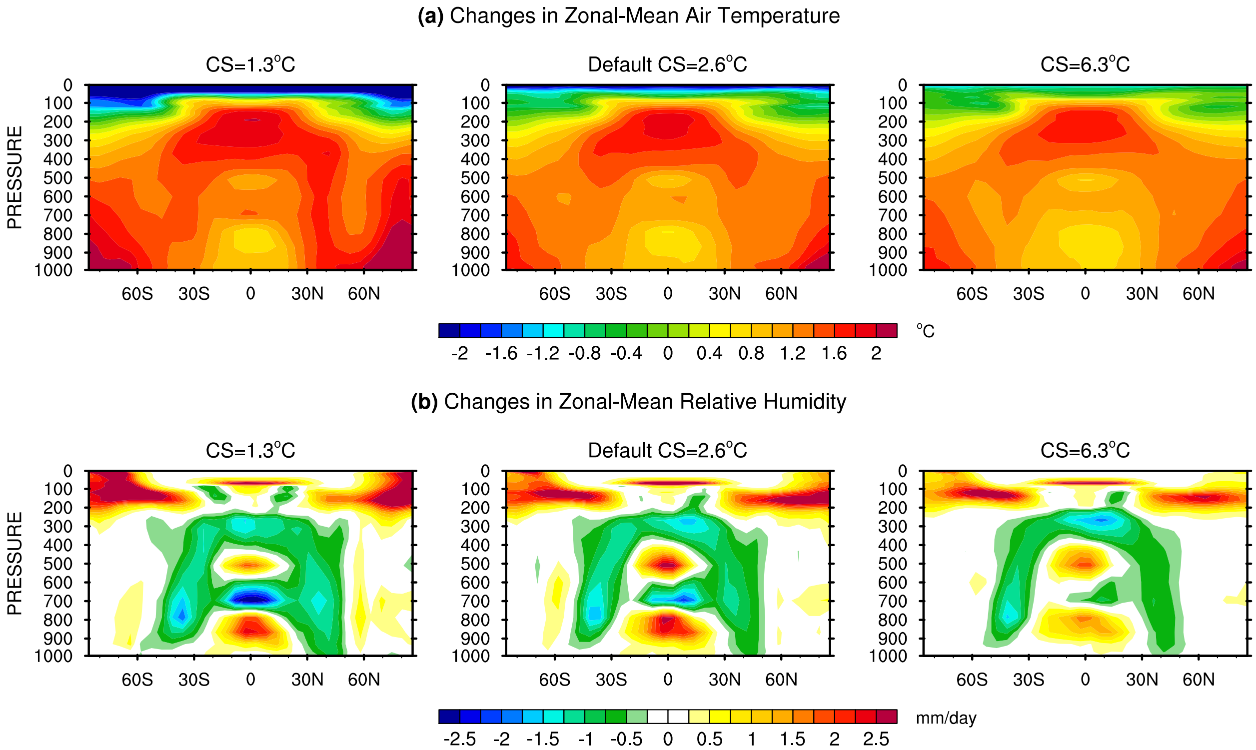

Figure 10. Same as Figure 9 but for **(a)** Zonal-Mean Air Temperature and **(b)** Zonal-Mean Relative Humidity.

particular, it shows that the version of CAM3 with the lowest climate sensitivity produces the strongest polar amplification relative to its global response. 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 version of CAM3 shows the opposite. This underlines the existence of different regional patterns of change obtained with the cloud radiative adjustment method. Despite these regional differences, the changes simulated by versions of CAM3 with a rather low and high climate sensitivity agree well with the changes simulated by the standard version of CAM3. **Figure 10** displays latitude-height cross sections of changes in zonal-mean air temperature and zonal-mean relative humidity. 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.

3.2 Comparison to CAM4 and CAM5 Simulations

In this section, we compare results of equilibrium doubled-CO_2 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. Andrew Gettelman (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°x2.5°, similar to that of CAM4 and CAM5. The climate sensitivity of the standard 2°x2.5° version of CAM3 is 2.2°C. Simulations with CAM3 with climate sensitivities of 3.1°C, 4.2°C 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 20-year (years 41-60) means from doubled-CO_2 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 clouds in simulations with the different versions of CAM (**Figure 11**), where differences for clouds used in the radiation calculations are shown for CAM3. Figure 11 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 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

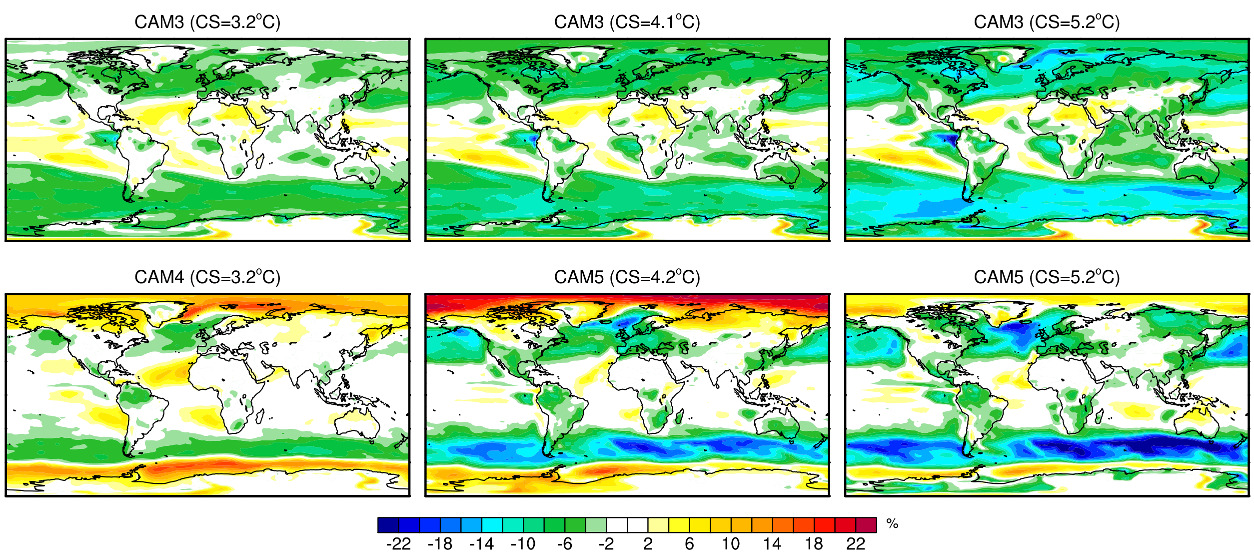

Figure 11. Changes in Low Clouds in response to a doubling of CO_2 concentrations **(bottom)** with CAM4 (CS=3.1°C) and CAM5 (CS=4.2°C and CS=5.1°C) and **(top)** with versions of CAM3 with matching climate sensitivities. Clouds used in the radiation calculations are shown for CAM3.

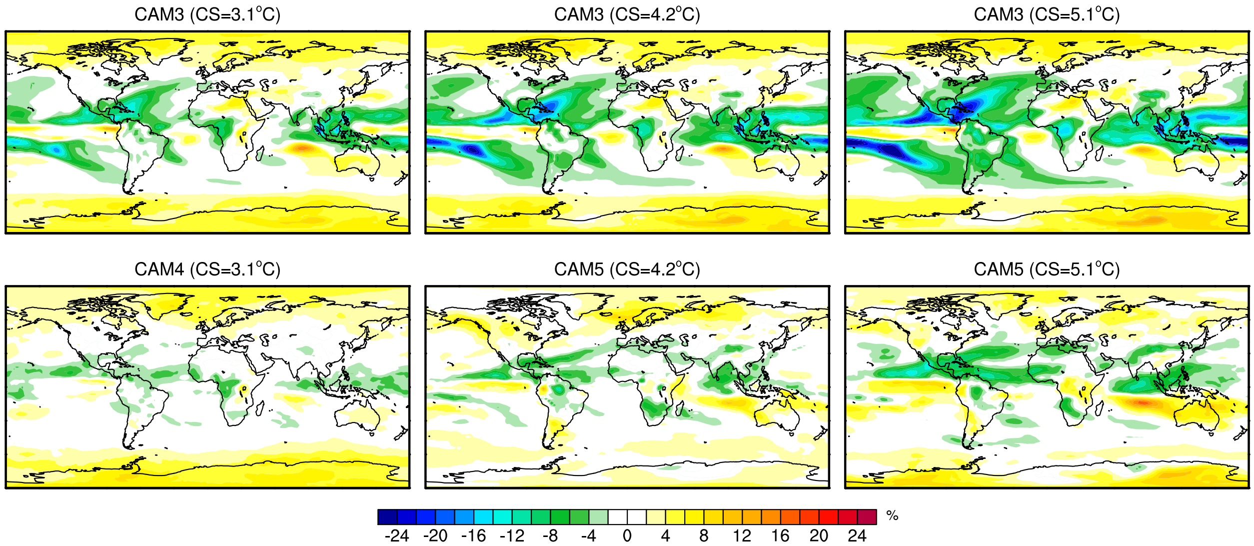

Figure 12. Same as Figure 11 but for High Clouds.

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 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.*, 2010b). The agreement over non polar regions is much better, especially between simulations with a high climate sensitivity. Changes in high clouds, shown in **Figure 12**, 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 11 and Figure 12 indicate 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 13 shows the changes in surface air temperature for all CAM3, CAM4 and CAM5 simulations. There is good agreement in the magnitude and spatial patterns of changes 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

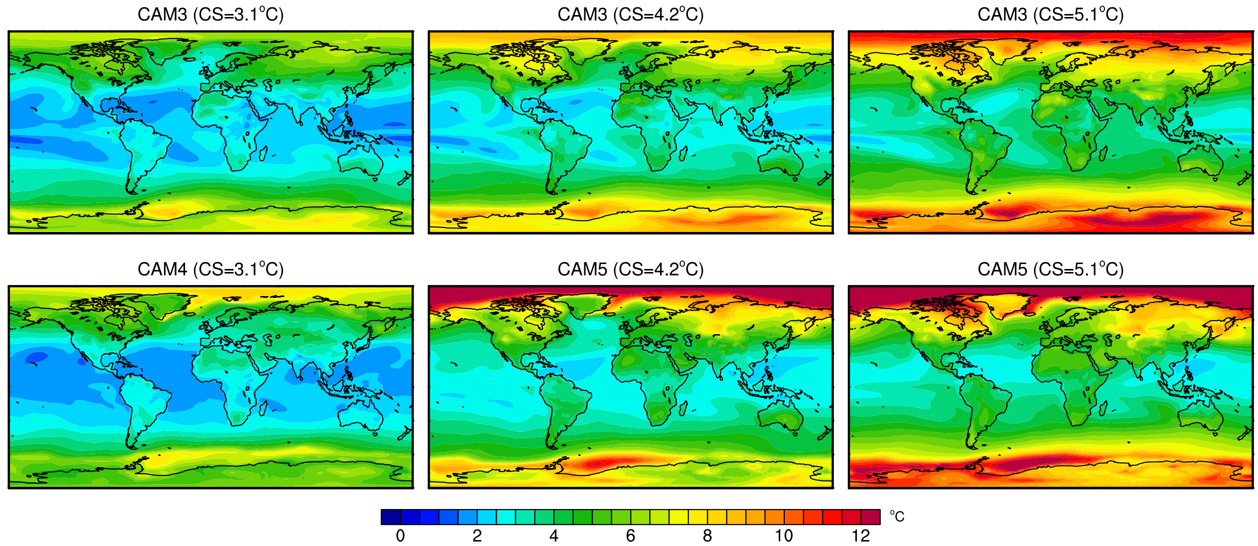

Figure 13. Changes in Surface Air Temperature in response to a doubling of CO_2 concentrations **(bottom)** with CAM4 (CS=3.1°C) and CAM5 (CS=4.2°C and CS=5.1°C) and **(top)** with versions of CAM3 with matching climate sensitivities.

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, Figure 13 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 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

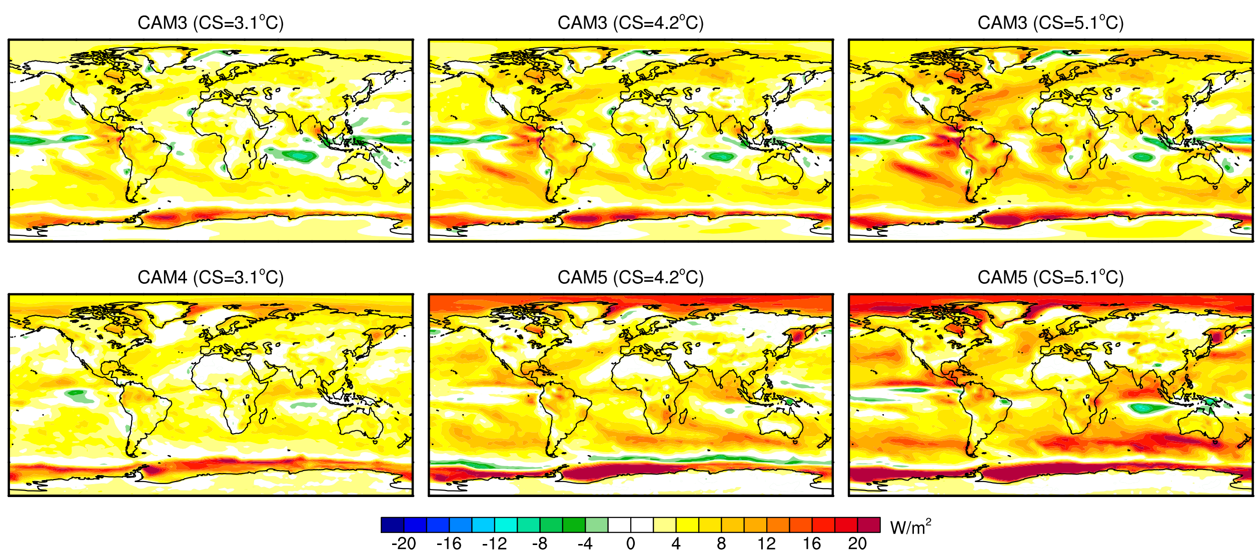

Figure 14. Same as Figure 13 but for Surface Net Radiative Flux.

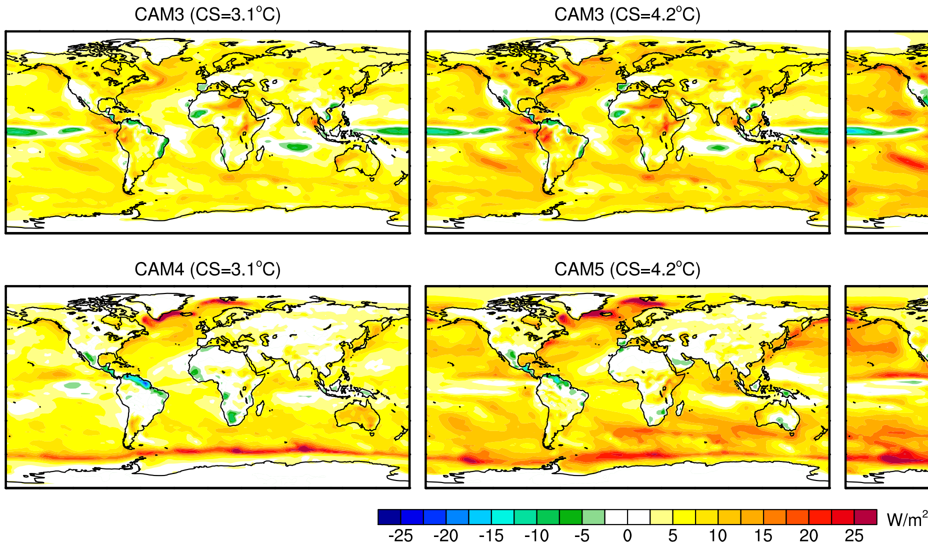

Figure 15. Same as Figure 13 but for Surface Latent Heat Flux.

discrepancy.

Changes in surface net radiation flux are shown in **Figure 14**. Once again, the largest differences 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 absorbed solar radiation while changes in the net longwave flux (not shown) are consistent between simulations with similar values of climate sensitivity. Elsewhere, the changes in surface net radiation flux match well, with a noticeably better agreement between CAM3 and CAM4 than between CAM3 and CAM5.

Changes in surface latent heat flux are displayed in **Figure 15**. The largest disparities include a larger increase in the polar region over the ocean in simulations with CAM4/CAM5 and a larger

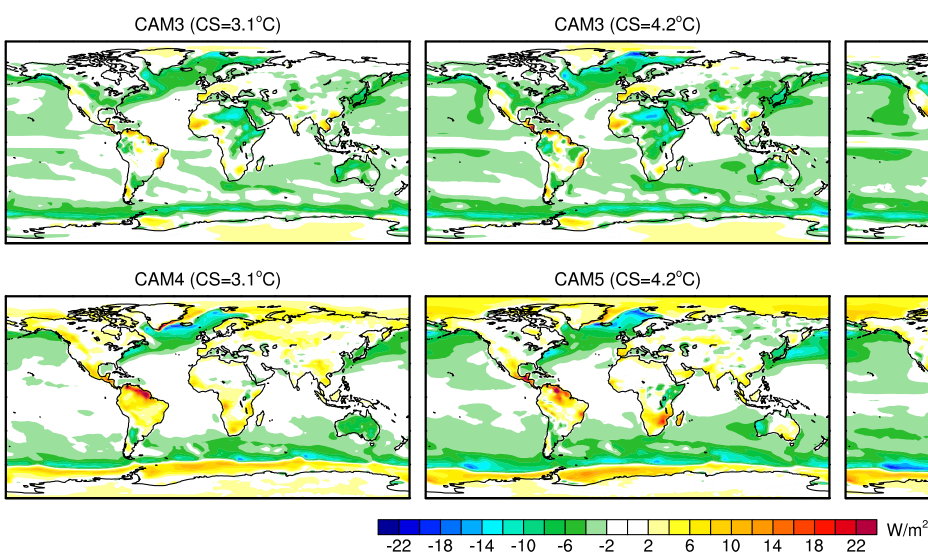

Figure 16. Same as Figure 13 but for Surface Sensible Heat Flux.

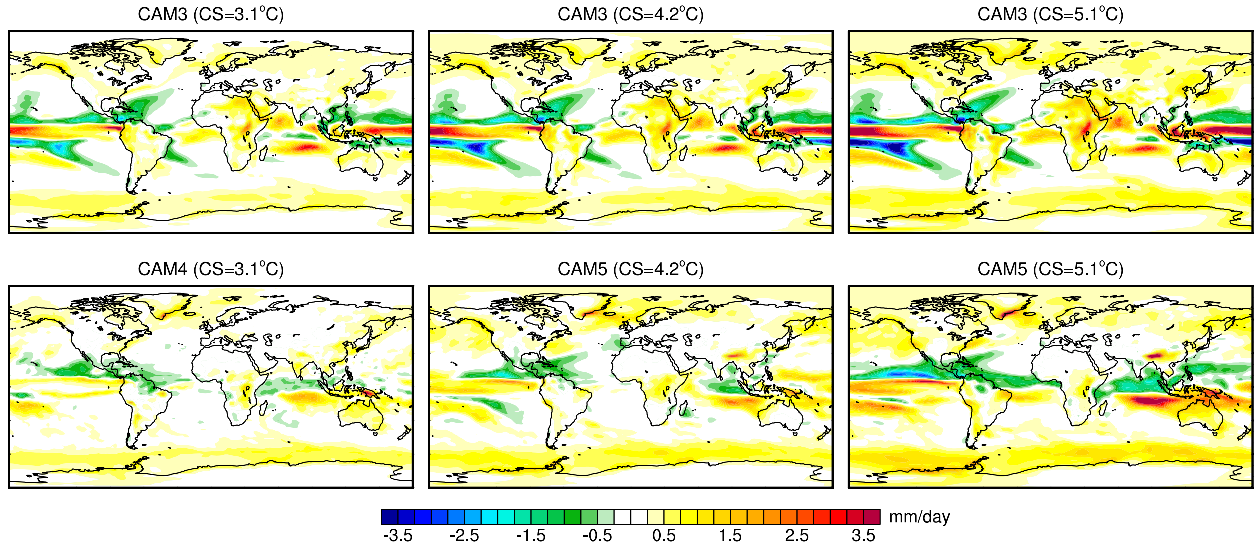

Figure 17. Same as Figure 13 but for Total Precipitation.

increase in evaporation over land in simulations with CAM3. These can be attributed to the differences in low clouds and sea ice mentioned previously and to the use of different land surface models, respectively. **Figure 16** shows changes in sensible heat flux. CAM4/CAM5 simulations 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, that are not present in the CAM4/CAM5 simulations. These differences likely have the same origin as the disparities in changes in surface latent heat flux. It is worth noting that the large increase in evaporation and large decrease in sensible heat flux over land, as well as the decrease in evaporation over the ocean in the tropics, are present in simulations with the standard version of CAM3.

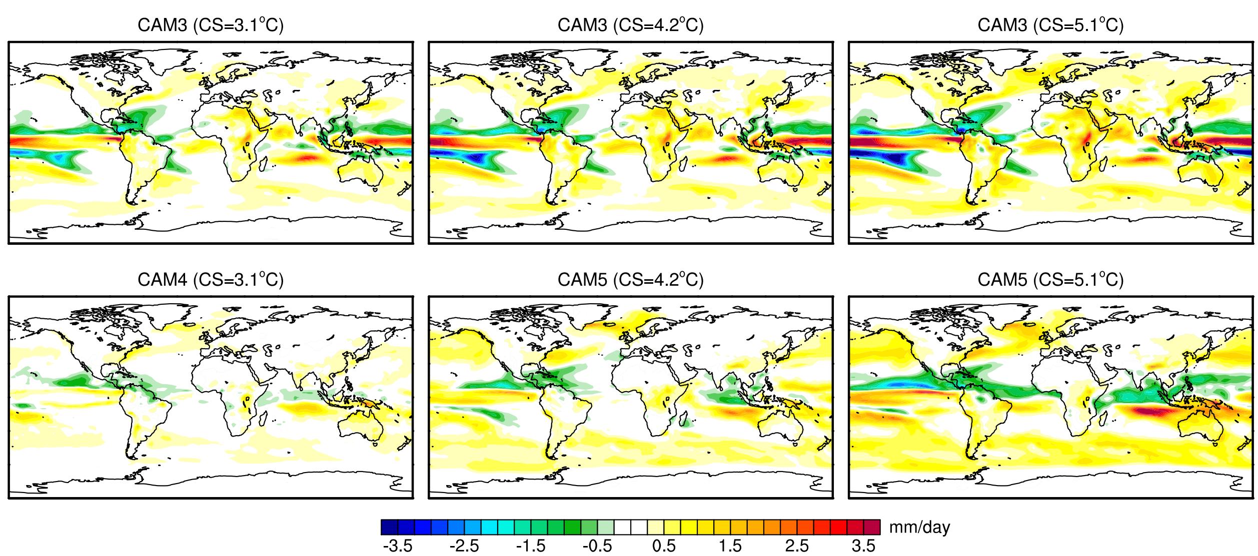

Figure 18. Same as Figure 13 but for Convective Precipitation.

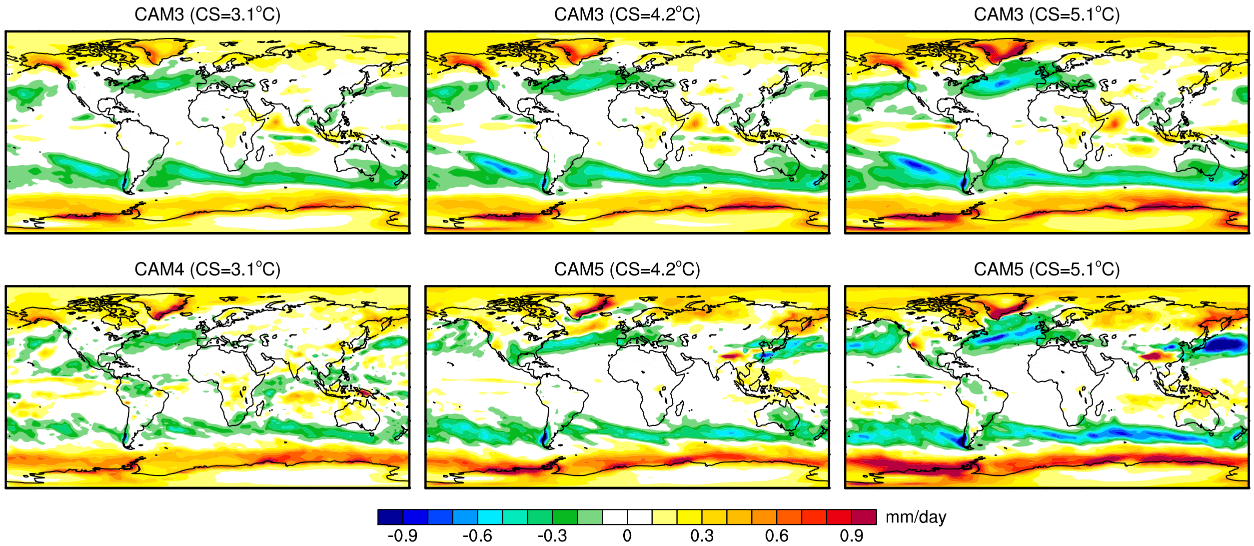

Figure 19. Same as Figure 13 but for Large-Scale Precipitation.

Finally, changes in total precipitation are shown in **Figure 17**. They are almost exclusively the result from changes in convective precipitation, shown in **Figure 18**, while changes in large-scale precipitation (**Figure 19**) are similar for all versions of CAM. Such differences are consistent with the differences in convection parameterizations between the various versions of CAM. This further demonstrates that the largest differences between the CAM3, CAM4 and CAM5 simulations 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 CONCLUSION

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, 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 20th 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, the cloud radiative adjustment method does not involve physically unrealistic changes in cloud cover.

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 CO_2 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. It should be noted that the perturbed physics approach could be combined with the cloud radiative adjustment method in order to produce any value of climate sensitivity within the wide range of uncertainty as well as cover the full uncertainty in regional patterns of climate change.

Overall, the results presented in this study show that the cloud 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 forcings. It can also be used to study uncertainty in future climate projections as well as uncertainty in the future response of various modes of variability, such El Niño/Southern Oscillation, under climate change.

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