A note on the effect of GCM tuning on climate sensitivity

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Abstract

A tuning experiment is carried out with the Community Atmosphere Model version 3, where the top-of-the-atmosphere radiative balance is tuned to agree with global satellite estimates from ERBE and CERES, respectively, to investigate if the climate sensitivity of the model is dependent upon which of the datasets is used. The tuning is done through alterations of cloud parameters that affect, for instance, the model cloud water content, but the difference in cloud water content between the two model configurations is found to be negligible compared to the wide spread of the same quantity in a number of state-of-the-art GCMs. The equilibrium climate sensitivities of the two model configurations differ by ca. 0.24 K, and both lie well within the range of present estimates of climate sensitivity in different GCMs. This indicates that it is possible to tune the model to either of the two satellite datasets without drastically changing the climate sensitivity. However, the study illustrates that the climate sensitivity is a product of choices of parameter values that are not well restricted by observations, which allows for a certain degree of arbitrariness in the estimates of climate sensitivity.

Keywords: tuning, GCM, climate sensitivity

1. Introduction

Satellite observations of the top-of-the-atmosphere (TOA) radiative budget are essential for restricting climate models. However, the observations are afflicted with errors and are not always in agreement with each other. This was made evident by, for example, Bender et al. (2006) where ERBE (Earth Radiation Budget Experiment) (Barkstrom 1984, Barkstrom and Smith 1986) and CERES (Clouds and Earth’s Radiant Energy System) (Wielicki et al. 1996, Smith et al. 2004) observations of the global albedo were compared with each other and with output from general circulation models (GCMs), displaying a difference in albedo at the top of the atmosphere of 0.01 (corresponding to ca. 3.4 W m$^{-2}$) between the two satellite estimates.

At present, climate models are tuned to achieve agreement with observations. This means that parameter values that are weakly restricted by observations are adjusted to generate good agreement with observations for those parameters that are better restricted, with the TOA radiative balance belonging to the latter category. However, with the discrepancy between the two satellites’ estimates of the TOA radiative fluxes, the choice of reference dataset for the tuning process is not obvious. To date, ERBE is commonly used rather than CERES (Kiehl et al. 1998, Hack et al. 2006, Roeckner et al. 2006), which was also indicated by Bender et al. (2006), who found a more than twice as large deviation in TOA albedo between a multi-model mean and CERES as between a multi-model mean and ERBE.

The tuning of TOA fluxes to agree with satellite observations is done mainly via cloud parameters, as they are often poorly restricted by observations. However, cloud parameterizations and parameter values therein are known to be of importance in determining the climate sensitivity in a GCM (Senior and Mitchell 1992, Murphy et al. 2004). Climate sensitivity is a quantification of how the climate system—modeled or real—responds to an imposed radiative forcing and is a key parameter in model projections of future climate change. Equilibrium climate sensitivity, studied here, is defined as the increase in global mean temperature resulting from a doubling of the atmospheric concentration of CO$_2$. The
true sensitivity of the climate system is not accurately known and the climate sensitivity of a GCM is an inherent feature of the model physics. In this study we investigate if and how the climate sensitivity of a GCM, via differences in certain cloud parameters, may be dependent on which satellite dataset it is tuned to, ERBE or CERES.

2. Experiment

According to both ERBE and CERES the amount of shortwave (SW) radiation absorbed by the Earth is larger than the amount of longwave (LW) radiation emitted, which would indicate a heating of the system. The measured radiative imbalance is of the order of 5 W m\(^{-2}\), and is somewhat larger for CERES than for ERBE (see on-line data quality summaries at http://eosweb.larc.nasa.gov for details). Imbalances of this magnitude are not realistic and may, for instance, be compared with estimates of the total radiative forcing from anthropogenic greenhouse gases of 2.6 W m\(^{-2}\) (IPCC 2007) and measurements of ocean heat storage, which indicate a heating representing less than 1 W m\(^{-2}\) since the mid-1950s (Levitus et al 2000, Willis et al 2004). In a GCM, a large radiative imbalance is not tolerable and, given that the LW side of the satellite budget is more trustworthy than the SW side (Kiehl and Trenberth 1997), we create two model configurations where the TOA radiative balances agree with ERBE and CERES LW fluxes, respectively.

The tuning is done in the atmospheric component of a coupled GCM, the Community Atmosphere Model, CAM3.1 (Collins et al 2006), employing a T42 spectral truncation, which corresponds to a horizontal resolution of 2.8\(^\circ\) × 2.8\(^\circ\). The model’s treatment of cloud microphysics and precipitation processes is described by Boville et al (2006).

The cloud microphysics of the model, as in any GCM, is highly parameterized and the tuning is carried out through alterations of parameter values in these physics descriptions. There are numerous non-restricted parameters that affect the model cloud properties and thereby the radiative fluxes, and hence there are numerous ways to tune the model to a chosen level of radiative balance. We modify a number of parameters that are commonly used for tuning (Hack et al 2006), including relative humidity thresholds for cloud formation, thresholds for autoconversion of liquid and ice to rain and snow, efficiency of autoconversion in convective and stratiform clouds, efficiency of precipitation evaporation and adjustment timescales associated with convection. Some combinations of parameter values can easily be ruled out, yielding features in cloud properties that strongly disagree with observations. For instance, the LW cloud radiative forcing in the ITCZ is found to be very sensitive to alterations in the efficiency of autoconversion in deep convective clouds and to the autoconversion threshold of ice to snow. In other cases, e.g. for the parameters determining the re-evaporation of rain, the radiative budget is too sensitive on the SW side compared to the LW side to suit our purposes. Still, within the realm of reasonable agreement with reality there is no unique way to reach a certain level of TOA radiative balance. The tuning process is pragmatic and the two model configurations discussed here are achieved through alterations of parameters subjectively chosen because they are found to give a relatively clear-cut effect on the radiative fluxes and result in the desired radiative balance levels without displaying unreasonable cloud properties.

The ERBE-like model configuration is tuned to a global mean TOA balance of ca. 234 W m\(^{-2}\) outgoing LW and net SW radiation. This is close to the default model configuration and only a slight alteration is made to the relative humidity threshold for formation of low clouds, which is decreased from 90% to 88%. The CERES-like model configuration is tuned to a global mean TOA balance of ca. 238 W m\(^{-2}\) outgoing LW and net SW radiation. This is further from the default model configuration and the new balance is achieved by altering the relative humidity threshold for forming high clouds (from 80% to 85%), the relative humidity threshold for forming low clouds (from 90% to 87%) and the rate of autoconversion of cloud droplets to raindrops in shallow convective clouds (from 2 × 10\(^{-4}\) to 1 × 10\(^{-3}\)). The magnitudes of these changes in parameter values do not exceed the differences in the default values of the same parameters in different horizontal resolution versions of the model (Collins et al 2004).

Increasing (decreasing) the relative humidity thresholds for formation of low and high clouds in the model results in a lower (higher) reflectivity, and thereby an increased (decreased) net SW radiation at the top of the atmosphere. It also leads to emission of LW radiation at a higher (lower) temperature, and thereby increased (decreased) outgoing LW radiation. Making the autoconversion of cloud droplets to rain more (less) efficient decreases (increases) the cloud amount and thereby leads to lower (higher) reflectivity and increased (decreased) net SW at the top of the atmosphere. The LW side of the budget is also affected, and the effective temperature, and thereby outgoing LW radiation, increased (decreased).

The two atmospheric model configurations are coupled to a slab ocean (Collins et al 2006) to calculate the equilibrium climate sensitivity, i.e. the change in global mean surface temperature at the equilibrium attained after an instantaneous doubling of the CO\(_2\) concentration. The reference simulations are branched after 16 years, and the reference and branch simulations extend for 30 years and 60 years, respectively, to ensure stable present-day and doubled-CO\(_2\) climates. The last 20 years of the reference and branch simulations are then compared with each other to determine the climate sensitivity in each case.

3. Results

3.1. Reference climates

The radiative balance levels in the two configurations differ by ca. 4 W m\(^{-2}\). Despite this difference in radiation balance level and their different tunings, the climates of the two simulations are similar in many respects. For instance, the latitudinal distribution of the surface temperature is hardly affected (figure 1) and remains in good agreement with observations. This can be seen as a necessary, but not sufficient, condition for a reasonably tuned model—surface temperatures are well
The global distribution of clouds is also similar in the two configurations, but the annual mean total cloud cover is somewhat lower in the CERES-tuned case (60% globally averaged, compared to 63% in the ERBE-tuned case). Figure 2 displays the distribution of total cloud cover in the two model simulations and the same quantity given by ISCCP observations (Rosow et al. 1996). The annual mean global mean total cloud cover is 67% according to ISCCP, and the main reason for the discrepancy relative to the model results is the greater observed cloud cover over the midlatitudes. The difference between the two model simulations lies primarily in high clouds and leads to maximum differences in LW cloud radiative forcing of ca. 10 W m$^{-2}$ locally in the ITCZ over the Indian and western Pacific Oceans (not shown). That the climates differ in cloud properties is expected, since this is where the changes have been made. The differences can also be exemplified by the grid-box total cloud water path, which is significantly smaller in the CERES-tuned case. The higher autoconversion rate in the CERES-tuned model lowers the cloud water content, as does the higher threshold for formation of high clouds, while the lower threshold for low cloud formation in that configuration somewhat raises the cloud water content.

The global mean cloud water paths (liquid phase only) are 134 g m$^{-2}$ and 119 g m$^{-2}$, respectively, in the ERBE- and CERES-tuned configurations. This difference between the two model configurations is still small compared to how widely the estimates of cloud water path vary between different GCMs. Figure 4 shows the global mean cloud water content in 18 coupled GCMs, simulating the 20th century’s climate (from the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset) and the estimates are seen to range from ca. 40 g m$^{-2}$ to ca. 270 g m$^{-2}$. The MODIS estimate of this quantity is, according to Penner et al. (2006), 193 g m$^{-2}$.

### 3.2. Climate sensitivity

Other satellite estimates over oceans only, derived from SSM/I (Special Sensor Microwave/Imager) with different retrieval algorithms, are 96 g m$^{-2}$ (Wentz 1997), 79 g m$^{-2}$ (Greenwald et al. 1993) and 48 g m$^{-2}$ (Weng and Grody 1994). NVAP (NASA Water Vapor Project), combining SSM/I data with other soundings, suggests a value of 78 g m$^{-2}$ as the global ocean mean (Randel et al. 1996). The corresponding ocean-only values for the two model simulations are 141 g m$^{-2}$ and 126 g m$^{-2}$ for the ERBE- and CERES-tuned configurations, respectively.

Due to the nature of the altered cloud parameters, the change in total cloud water content (liquid and ice phase) is primarily due to the change in liquid water path. The global mean total cloud water paths are 152 g m$^{-2}$ and 136 g m$^{-2}$, respectively, in the ERBE- and CERES-tuned configurations. This difference between the two model configurations is still small compared to how widely the estimates of cloud water path vary between different GCMs. Figure 4 shows the global mean cloud water content in 18 coupled GCMs, simulating the 20th century’s climate (from the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset) and the estimates are seen to range from ca. 40 g m$^{-2}$ to ca. 270 g m$^{-2}$. The MODIS estimate of this quantity is, according to Penner et al. (2006), 193 g m$^{-2}$.

Figure 5 shows the evolution of the surface temperature after the branching (i.e. the doubling of the CO$_2$ concentration) in the two cases. The difference in global mean temperature for the last 20 years of the two branch simulations is statistically significant at the 95% level, according to a Mann–Whitney
Figure 2. Global distribution of total cloud cover (%) for (a) the ERBE-tuned reference simulation (10-year mean), (b) the CERES-tuned reference simulation (10-year mean) and (c) ISCCP D2 data from 1983 to 2001.

Figure 3. 10-year mean global distribution of liquid phase cloud water path (g m$^{-2}$) for (a) the ERBE-tuned reference simulation and (b) the CERES-tuned reference simulation.

test, and the equilibrium climate sensitivity ($\Delta T_{2xCO_2}$) is found to be 2.50 K for the ERBE-tuned model and 2.26 K for the CERES-tuned model.

Although the sensitivity of the model tuned to CERES is lower than that of the ERBE-tuned model by 0.24 K, the tuning-induced difference is small when compared to estimates of equilibrium climate sensitivity in leading GCMs that span from 2.0 to 4.5 K (IPCC 2007). The difference is also well within the range of differences in climate sensitivity presented by Stainforth et al (2005), whose results, based on a large
ensemble of model versions, are centered around 3.4 K, but range from less than 2 K to more than 11 K. However, rather than constraining the model to a certain level of radiative balance at the TOA, as in the present study, Stainforth et al (2005) vary model parameters within their respective estimated uncertainty ranges and the range of climate sensitivities found may therefore be seen as manifestations of maximum uncertainty, given that the individual parameter uncertainties are reasonably estimated.

The difference between the ERBE-tuned and CERES-tuned model configurations can also be compared to the results of Kiehl et al (2006), who investigated the dependence of climate sensitivity on horizontal resolution of the CAM. They found that $\Delta T_{2 \times CO_2}$ increased from 2.32 K for a T31 resolution, to 2.47 K for a T42 resolution and 2.71 K for a T85 resolution, i.e. variations of the same order of magnitude as that found here, that may partly be explained by the differences in tuning necessary to achieve energy balance at the different resolutions (Hack et al 2006).

4. Conclusions

We have shown that it is possible to tune the Community Atmosphere Model to CERES, with similar realism as when tuning it to ERBE, without largely impacting the model’s climate sensitivity. Whether or not tuning to CERES is a better choice than tuning to ERBE is not a matter we discuss here, and our results do not make one set of observations more credible than the other. There are, however, documented improvements in CERES fluxes relative to ERBE fluxes, particularly related to reductions in angular biases, due to improved angular distribution models used to convert radiances to radiative fluxes (see, e.g., Wong et al 2000, Wielicki et al 1996). The different tuning does alter the climate sensitivity of the model, but the difference between $\Delta T_{2 \times CO_2}$ for the ERBE-tuned and the CERES-tuned configurations is not of the same order of magnitude as the range of climate sensitivities in state-of-the-art GCMs, and it is subtle compared to the extreme uncertainty in climate sensitivity due to model configuration that has previously been indicated. Rather, the difference is similar in size to that found between climate sensitivities for different horizontal resolutions of the same model.

Although this limited study offers no conclusive evidence, it indicates that the CAM is rather robust to tuning changes and that climate sensitivity is not strongly dependent on what level the TOA radiative balance is tuned to. This is a reassuring conclusion—practising tuning is necessary for achieving agreement with observations in key parameters, and possible since there are parameters that are still not well restricted by measurements. A strong dependence of climate sensitivity on TOA radiative balance level through the parameters determining it would make predictions of future warming no less arbitrary than the choice of dataset to tune the model to.

Nonetheless, the difference in climate sensitivity should not be repudiated. Clearly, the uncertainty in cloud parameters together with the ambiguity in the TOA radiative budget observations allow for differing model configurations and subsequently differing climate sensitivities, for which there is presently no way to determine which is more correct. The small magnitude of the difference must not be used as an excuse for not continuing to refine the measurements of the TOA radiative balance or imbalance and definitely not as an excuse for not making further attempts to restrict free parameters like cloud water content in models. The two realizations studied here may or may not be representative of a larger ensemble of differently tuned model configurations, but the fact that they display a difference in climate sensitivity calls for caution in the unavoidable tuning process.

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References

Barkstrom B R 1984 The earth radiation budget experiment (ERBE) Bull. Am. Meteorol. Soc. 65 1170–85
Barkstrom B R and Smith G L 1986 The earth radiation budget experiment: science and implementation Rev. Geophys. 24 379–90
Bender F A-M, Rodhe H, Charlson R J, Ekman A M-L and Loeb N 2006 22 views of the global albedo—comparison between 20 GCMs and two satellites Tellus A 58 320–30
Boville B A, Rasch P J, Hack J J and McCaa J R 2006 Representation of clouds and precipitation processes in the Community Atmosphere Model Version 3 (CAM3) J. Clim. 19 2184–98
Collins W D et al 2004 Description of the NCAR Community Atmosphere Model (CAM3) NCAR Technical Note NCAR/TN-464+STR
Collins W D, Rasch P J, Boville B A, Hack J J, McCaa J R, Williamson D L, Brumley B P, Bitz C M, Lin S-J and Zhang M 2006 The formulation and atmospheric simulation of the Community Atmosphere Model version 3 (CAM3) J. Clim. 19 2144–61
Greenwald T J, Stephens G L, Vander Haar T H and Jackson D L 1993 A physical retrieval of cloud liquid water over the global oceans using special sensor microwave/imager (SSMI) observations J. Geophys. Res. 98 18471–88
Hack J J, Caron J M, Danabasoglu G, Oleson K W, Bitz C and Truesdale J E 2006 CCSM-CAM3 climate simulation sensitivity to changes in horizontal resolution J. Clim. 19 2267–89
IPCC 2007 Climate change 2007: the physical science basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averet, M Tignor and H L Miller (Cambridge: Cambridge University Press)
Kalnay E et al 1996 The NCEP/NCAR 40-year reanalysis project Bull. Am. Meteorol. Soc. 77 437–70
Kiehl J T, Hack J J and Hurrell J W 1998 The energy budget of the NCAR Community Climate Model: CCM3 J. Clim. 11 1151–78
Kiehl J T, Shields C A, Hack J J and Collins W D 2006 The climate sensitivity of the Community Climate System Model Version 3 (CCSM3) J. Clim. 19 2584–96
Kiehl J T and Trenberth K E 1997 Earth’s annual global mean energy budget Bull. Am. Meteorol. Soc. 78 197–208
Levitus S, Antonov J I, Boyer T P and Stephens C 2000 Warming of the world ocean Science 287 2225–9
Murphy J M, Sexton D M H, Barnett D N, Jones G S, Webb M J, Collins M and Stainforth D A 2004 Quantification of modelling uncertainties in a large ensemble of climate change simulations Nature 430 768–72
Penner J E, Quaas J, Storelvmo T, Takemura T, Boucher O, Guo H, Kirkevåg A, Kristjánsson J E and Seland Ø 2006 Model intercomparison of indirect aerosol effects Atmos. Chem. Phys. 6 3391–405
Platnick S, King M D, Ackerman S A, Menzel W P, Baum B A, Riedi J C and Frey R A 2003 The MODIS cloud products: algorithms and examples from Terra IEEE Trans. Geosci. Remote Sens. 41 459–73
Randel D L, Vander Haar T H, Ringerud M A, Stephens G L, Greenwald T J and Combs C L 1996 A new global water vapor dataset Bull. Am. Meteorol. Soc. 77 1233–46
Roeckner E, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kornblueh L, Manzini E, Schlese U and Schulzweida U 2006 Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model J. Clim. 19 3771–91
Rossow W B, Walker A W, Beuschel D E and Roiter M D 1996 International Satellite Cloud Climatology Project (ISCCP) Documentation of New Cloud Datasets WMO/TD-No. 737 World Meteorological Organization
Senior C A and Mitchell J F B 1992 Carbon dioxide and climate: the impact of cloud parameterization J. Clim. 6 393–418
Smith G L, Wielicki B A, Barkstrom B R, Lee R B, Priestly K J, Charlock T P, Minnis P, Kratz D P, Loeb N and Young D F 2004 Clouds and the Earth radiant energy system: an overview Adv. Space Res. 33 1125–31
Stainforth D A et al 2005 Uncertainty in predictions of the climate response to rising levels of greenhouse gases Nature 433 403–6
Wielicki B A, Barkstrom B R, Harrison E F, Lee R B, Smith L and Cooper J E 1996 Clouds and the Earth’s radiant energy system (CERES): an earth observing system experiment Bull. Am. Meteorol. Soc. 77 853–68
Willis J K, Roemmich D and Cornuelle B 2004 Interannual variability in upper ocean heat content, temperature and thermosteric expansion on global scales J. Geophys. Res. 109 C12036
Wentz F J 1997 A well-calibrated ocean algorithm for special sensor microwave imager J. Geophys. Res. 99 25535–51
Wentz F J 1997 A well-calibrated ocean algorithm for special sensor microwave/imager J. Geophys. Res. 102 8703–18
Wong T, Young M, Haeffelin M and Weckmann S 2000 Validation of the CERES/TRMM ERBE-like monthly mean clear-sky longwave dataset and the effects of the 1998 ENSO event J. Clim. 13 4256–67