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On the Correlation between Forcing and Climate Sensitivity

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On the Correlation between Forcing and Climate Sensitivity

Andrei P. Sokolov*

Abstract

The possible correlation between climate sensitivity and radiative forcing is studied using versions of the NCAR Community Atmospheric Model (CAM) model with different climate sensitivities. No such correlation was found for the CO_2 forcing. A weak correlation for the direct sulfate aerosol forcing is associated with differences in cloud cover in control climate simulations with different versions of the model. Presented results suggest that correlation between sensitivity and radiative forcing in the 20th century simulations with different AOGCMs is not a reflection of physical reality but is a result of different treatments of forcing agents, primarily aerosols.

Contents

1. INTRODUCTION

Kiehl (2007), Knutti (2008) and Anderson *et al*. (2010) showed that strengths of radiative forcing in the 20th century simulations with different AOGCMs are correlated with climate sensitivities of these models. They, however, disagree on the nature of such correlation.

Kiehl (2007) showed that differences in the total radiative forcing between AOGCMs are primarily due to differences in the aerosol forcing used by these models. Knutti (2008) suggests that choices concerning aerosol treatment (*e.g.*, whether to include indirect aerosol effect) might have been made based on the results of historical climate change simulations. Knutti (2008) also indicated a possibility of correlation between indirect aerosol effect and climate sensitivity, but noted that only 7 out the analyzed 23 models included this effect. On the other hand, Anderson *et al.* (2010) seem to suggest an existence of physically based correlation between radiative forcing and climate sensitivity. In particular, they state that radiative forcing due to doubling of the CO_2 concentration will vary over a very wide range depending on the model climate sensitivity. They also state that not taking this correlation into account in probabilistic projections of climate change is likely to increase uncertainty of such projections.

In the present study the relation between climate sensitivity and radiative forcing is investigated by means of numerical simulations using three versions of the CAM3 model with different climate sensitivities. The treatment of different forcing agents is identical in simulations with different CAM3 versions. Such simulations allow to test whether the found correlation between forcing and sensitivity is physically based or is an artifact of the different forcing representations in different models.

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2. MODEL AND METHOD

The NCAR Community Atmospheric Model, version 3 (CAM3) (Collins *et al*., 2004) with T21 resolution was used in this study. Standard version of this model has sensitivity of 2.6^{o}C to the doubling of CO_2 concentration. Versions of the model with higher and lower sensitivity were obtained by changing the relative humidity of cloud formation for high and low clouds. As was noted by Sanderson (2009), CAM3 is rather insensitive to changes in the model's parameters. As a result sensitivities of these two versions of CAM3 are not very different from the standard, namely 2.9 and 2.0^{o}C.

At first, two 90 year transient simulations were carried out with the standard version of the CAM3 coupled to an anomaly diffusing ocean model (Sokolov *et al*., 2003). During the first ten years of each simulation concentrations of GHGs and other forcing agents were held fixed. After that, in the first simulation the model was forced by the CO_2 concentration increasing at 1% per year rate. In the second simulation the model was forced by an increase in the loading of sulfate aerosol, namely the default loading was scaled in time with a scaling coefficient increasing from 1 to 5 in 70 years.[†]

The sea surface temperature (SST) and sea ice distributions obtained in these two simulations were then used to evaluate the radiative forcing and implied ocean heat uptake following the approach of Anderson *et al.* (2010) using a set of AMIP type simulations.

Two simulations were performed with each version of the CAM3 for each forcing case. In the first simulation, referred to as the AMIP simulation, the atmospheric model was forced by prescribed changes in SST and sea ice with the forcing fixed at its initial value. In the second simulations (AMIP+ATM) the model was forced by both changes in SST and corresponding forcing. Changes in the radiative balance (H) at the top of the atmosphere (TOA) in the first simulation can be written as:

$$\Delta H_{AMIP} = -\lambda \cdot \Delta T_{AMIP}, \tag{1}$$

where λ is a feedback parameter and T is surface air temperature (SAT). Changes in the radiative balance at the TOA in the second simulation equal

$$\Delta H_{AMIP+ATM} = F - \lambda \cdot \Delta T_{AMIP+ATM} = OHU, \tag{2}$$

where F is radiative forcing and OHU is an implied ocean heat uptake required for the given version of atmospheric model to simulate prescribed changes in SAT.

Value of λ can be estimated by regressing H_{AMIP} against ΔT_{AMIP}. Spencer and Braswell (2008), using a simple box model, demonstrated that the values of the feedback parameter estimated in such a way can be biased. Murphy and Forster (2010), however, showed that the accuracy of this approach is significantly higher than implied by Spencer and Braswell (2008). As will be shown below, climate sensitivities calculated from the results of AMIP simulations are very close to those estimated from the equilibrium 2xCO_2 simulations with a slab ocean model.

[†] The CAM3 version available at NCAR website has a scaling option for carbon but not for sulfate aerosol. Scaling of the sulfate aerosol was implemented by Erwan Monier at MIT.

Finally, radiative forcing can be expressed from equation (2) as

$$F = \Delta H_{AMIP+ATM} + \lambda \cdot \Delta T_{AMIP+ATM} \quad (3)$$

Anderson *et al.* (2010), when estimating radiative forcing, ignored a small difference between ΔT_{AMIP} and $\Delta T_{AMIP+ATM}$. In simulations discussed below this difference is larger due to stronger forcing (**Figure 1**) and should be accounted for. All variables are plotted as a difference from the average over the first ten years of simulation, during which forcing was held fixed. The averages of three simulations from different initial conditions are shown in **Figures 2** and **3**.

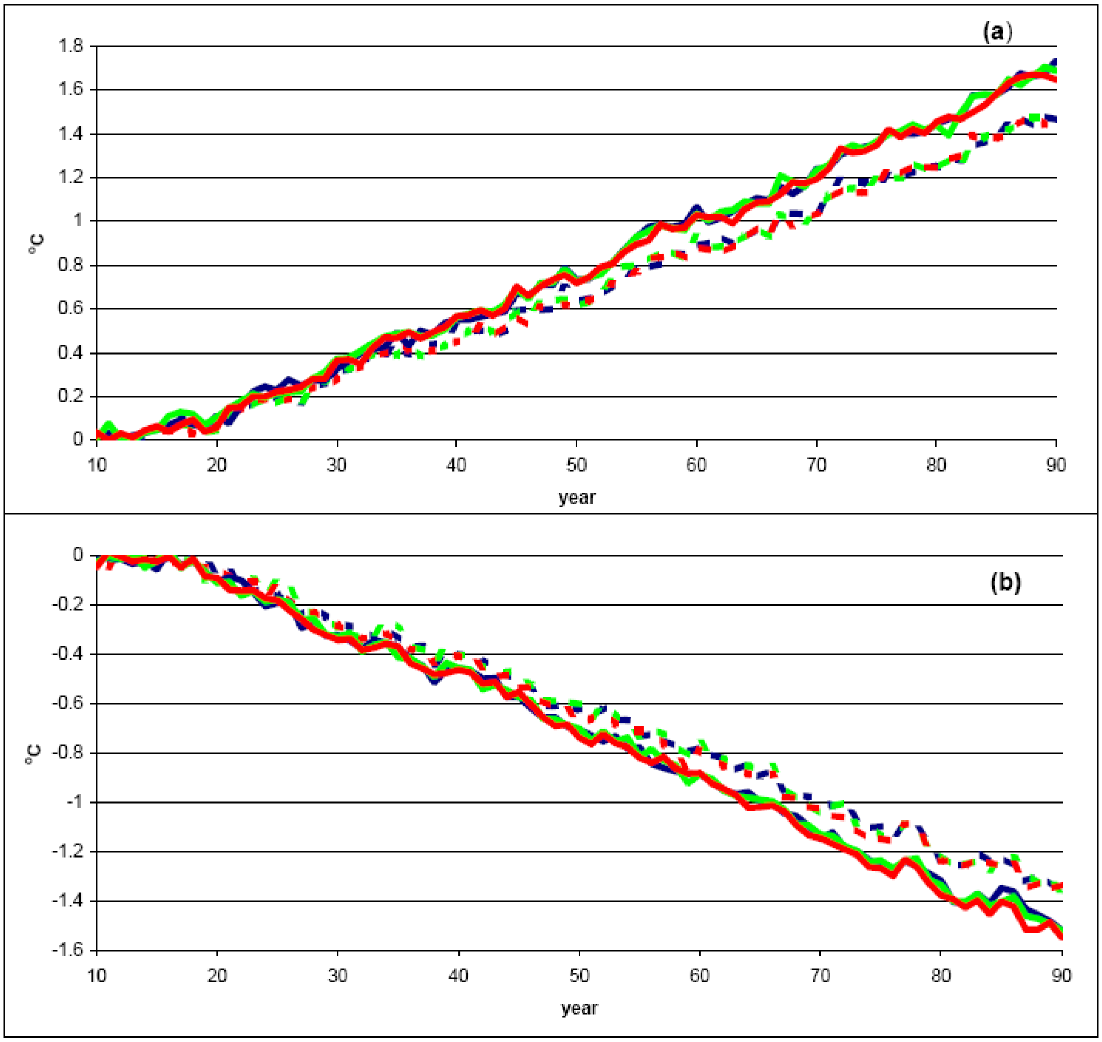

Figure 1. SAT changes in the AMIP (dashed lines) and AMIP+ATM (solid lines) simulations for (a) CO_2 and (b) sulfate aerosol forcings. Blue, green and red lines are for the model version with high, standard and low sensitivity respectively.

Use of the SST from model simulations with changes in CO_2 and sulfate aerosol, described above, has some advantages compared to the use of the observed 20th century SST. First, simulated SST changes are significantly larger than observed, while inter-annual variability is smaller. This leads to higher accuracy of calculations, as well as amplifies the difference between simulations with different model versions. Second, it allows studying separately forcing associated with different forcing agents.

3. RESULTS AND CONCLUSIONS

Figure 2 shows results of the simulations for the CO_2 forcing case. Changes in the radiation at the TOA (Figure 2a) are noticeably different in the simulations with different versions of the model. Values of climate sensitivity ($S=\lambda^{-1}$) derived for AMIP simulations are given in **Table 1**.

Table 1. Values of climate sensitivity for different CAM3 versions evaluated from AMIP simulations for CO_2 and sulfate aerosol forcing cases and from equilibrium simulations with doubled CO_2 concentration.

Simulation	HS	SS	LS
AMIP CO2	0.77	0.62	0.50
AMIP aerosol	0.73	0.62	0.54
Equilibrium 2xCO2	0.75	0.67	0.53

On the other hand, the forcing associated with CO_2 increase (Figure 2b and **Table 2**) is practically identical in all simulations being equal to about 3.8 W/m^2 at the time of CO_2 doubling. According to results of Anderson *et al*. (2010), it should be changing from 3.7 to 5.4 W/m^2 (see their Figure 7). Sensitivities for 2xCO_2 case (Table 1) were calculated using forcing at the time of CO_2 doubling estimated from the equation (3) and changes in SAT from equilibrium simulations with a slab ocean model. As can be seen they are very close to the estimates obtained from AMIP simulations, confirming validity of the regression approach.

Table 2. Values of radiative forcing for different CAM3 versions evaluated from AMIP simulations for CO_2 and sulfate aerosol forcing cases for years 76-85 and forcing for 5 time aerosol loading calculated in the control climate simulations.

Simulation	HS	SS	LS
AMIP CO2	3.88	3.73	3.74
AMIP aerosol	-3.60	-3.32	-3.17
Control simulation	-3.63	-3.37	-3.27

The implied heat uptake by the deep ocean, required to simulate imposed changes in SAT (Figure 2c), increases with climate sensitivity, as should be expected for identical radiative forcing.

Simulations with changes in the sulfate aerosol loading do show some dependency between forcing and climate sensitivity (Figure 3b). The dependency is, however, rather weak and does not eliminate differences in implied ocean heat uptake (Figure 3c).

As noted above, sensitivity of the CAM3 model was changed by varying parameters affecting cloud formation. As a result cloud cover in the control simulations with different model versions is rather different. This is a main reason for the differences in the sulfate aerosol forcing. The values of the aerosol forcing evaluated from AMIP simulations at the time of fivefold increase in aerosol loading are very similar to the values of the forcing calculated in the control climate simulations by means of passive radiation calculation (Table 2). If different model parameters had been used for changing model sensitivity this dependency might not have existed. There are, however, studies indicating a correlation between climate sensitivity and cloud cover in control climate simulations for some GCMs (e.g. Volodin, 2008; Yokohate *et al*., 2010), which can lead to weak correlation between aerosol forcing and climate sensitivity. It should be noted that CAM3 does not include indirect aerosol effects.

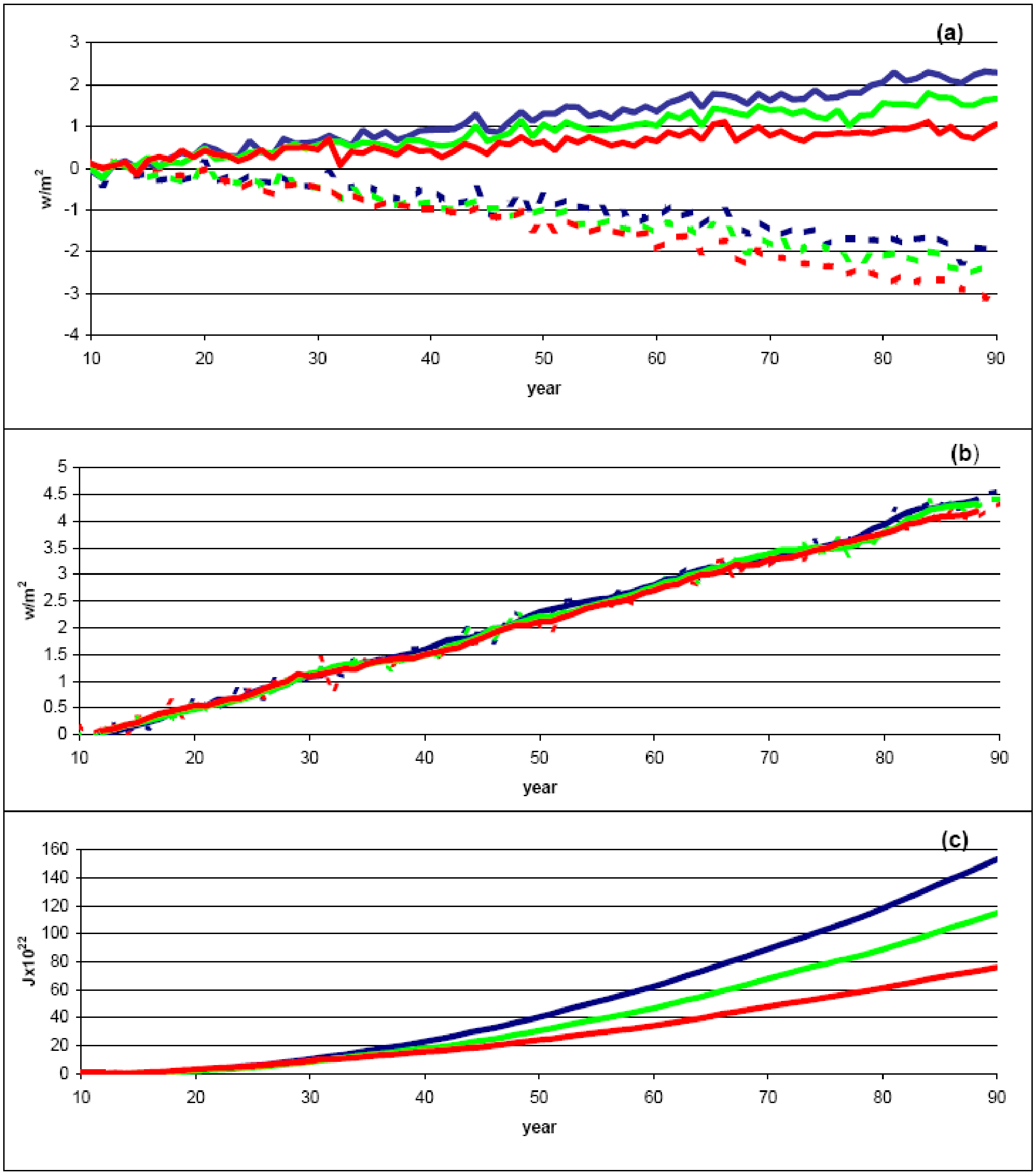

Figure 2. (a) Changes in the radiative balance at the TOA in the AMIP (dashed lines) and AMIP+ATM (solid lines) simulations;(b) annual radiative forcing (dashed lines) and five years running mean (solid lines); (c) implied cumulative heat uptake by the ocean for the CO_2 forcing case. Blue, green and red lines are for the model version with high, standard and low sensitivity respectively.

Results presented above suggest that there is no physically based correlation between radiative forcing and climate sensitivity. When forcings associated with different forcing agents are treated in the identical way such correlation is not present for CO_2 (and most likely other GHGs, such as CH_4 and N_20) forcing and is rather weak for an aerosol forcing. Correlation between forcing and sensitivity in the 20th century simulations with different AOGCMs found in the number of recent studies (Kiehl, 2007; Knutti, 2008; Anderson *et al*., 2010) is likely a result of different treatment of forcings, primarily aerosol forcing.

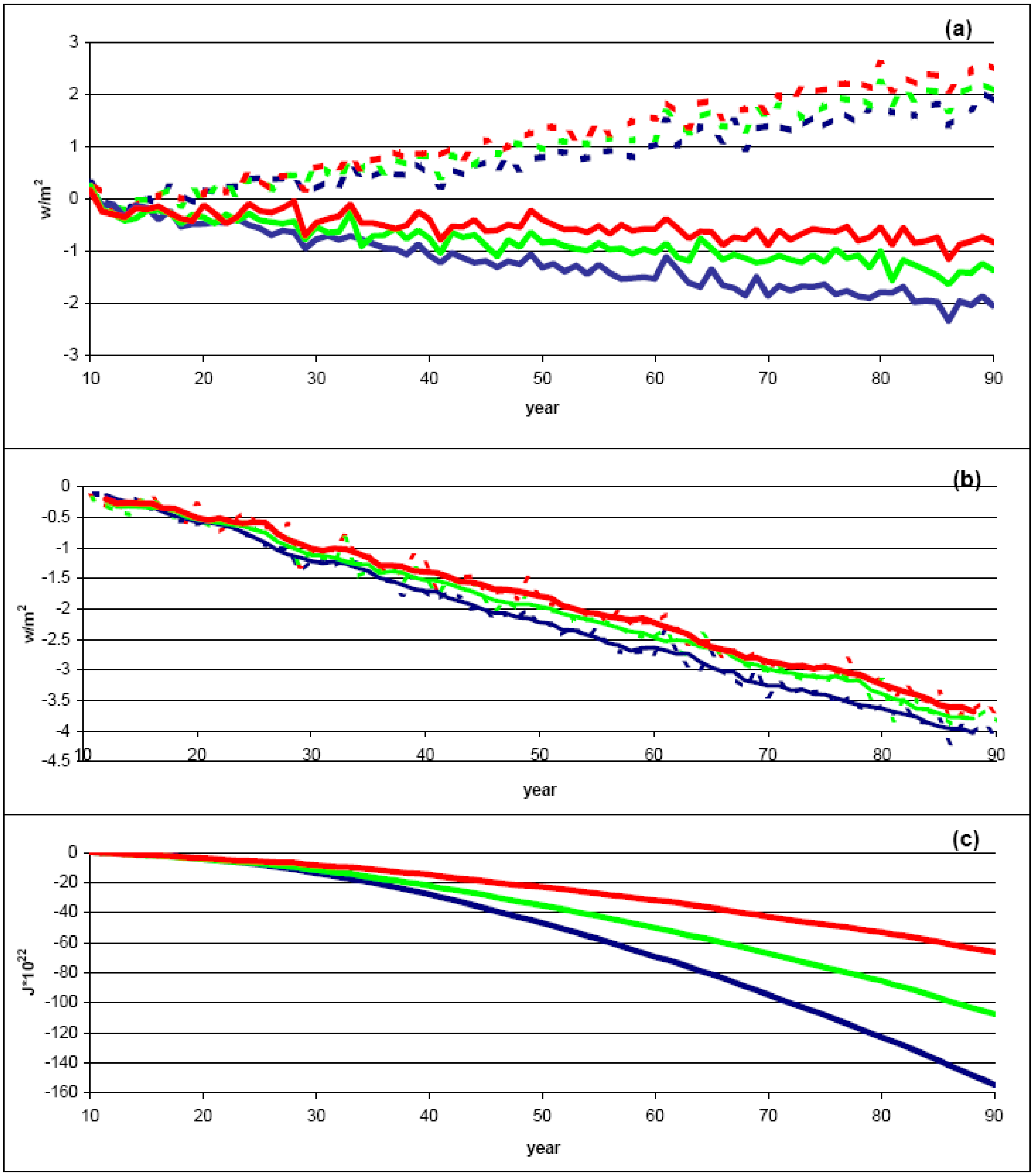

Figure 3. The same as Figure 2, but for sulfate aerosol forcing.

As have been already stated by Knutti (2008), an adjustment of aerosols forcing based on the results of historical climate change simulations is a completely legitimate approach. Probability distributions for the strength of aerosol forcing and climate parameters defining the model response to the forcing, e.g. climate sensitivity and the rate of heat uptake by the ocean, obtained with models of intermediate complexity based on the consistency between simulated and observed 20th century climates (Knutti *et al*., 2002; Forest *et al*., 2006), show significant correlation between parameters. Uncertainty in GHGs and other non-aerosol forcings are ignored in these studies because they are much smaller than uncertainty in aerosol forcing (Forster *et al*., 2007)

Correlation between climate parameters should be (and is) taken into account in probabilistic projections of future climate change (Webster *et al*., 2003; Knutti *et al*., 2005; Sokolov *et al*., 2009).

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(For the complete list see http://globalchange.mit.edu/sponsors/current.html).

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