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Twentieth century climate model response and climate sensitivity

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[1] Climate forcing and climate sensitivity are two key factors in understanding Earth's climate. There is considerable interest in decreasing our uncertainty in climate sensitivity. This study explores the role of these two factors in climate simulations of the 20th century. It is found that the total anthropogenic forcing for a wide range of climate models differs by a factor of two and that the total forcing is inversely correlated to climate sensitivity. Much of the uncertainty in total anthropogenic forcing derives from a threefold range of uncertainty in the aerosol forcing used in the simulations. **Citation:** Kiehl, J. T. (2007), Twentieth century climate model response and climate sensitivity, *Geophys. Res. Lett.*, *34*, L22710, doi:10.1029/2007GL031383.

1. Introduction

[2] Understanding the climate of the past is an important aspect to our ability to predict Earth's future climate. Three dimensional global climate models are the most comprehensive tools available to simulate Earth's past, present and future climates. Methods of testing these models with observations form an important part of model development and application. Over the past decade one such test is our ability to simulate the global anomaly in surface air temperature for the 20th century. A number of observational reconstructions of the temporal evolution of this climatically important quantity have been created [*Jones et al.*, 1999]. Climate model simulations of the 20th century can be compared in terms of their ability to reproduce this temperature record. This is now an established necessary test for global climate models. Of course this is not a sufficient test of these models and other metrics should be used to test models, for example the ability to simulate the evolution of ocean heat uptake over the later part of the 20th century [*Levitus et al.*, 2001; *Barnett et al.*, 2001], or a models ability to simulate trends in various modes of variability. All of these can be viewed as necessary test for climate models.

[3] A review of the published literature on climate simulations of the 20th century indicates that a large number of fully coupled three dimensional climate models are able to simulate the global surface air temperature anomaly with a good degree of accuracy [*Houghton et al.*, 2001]. For example all models simulate a global warming of 0.5 to 0.7°C over this time period to within 25% accuracy. This is viewed as a reassuring confirmation that models to first order capture the behavior of the physical climate system and lends credence to applying the models to projecting future climates.

[4] One curious aspect of this result is that it is also well known [*Houghton et al.*, 2001] that the same models that agree in simulating the anomaly in surface air temperature differ significantly in their predicted climate sensitivity. The cited range in climate sensitivity from a wide collection of models is usually 1.5 to 4.5°C for a doubling of CO_2, where most global climate models used for climate change studies vary by at least a factor of two in equilibrium sensitivity.

[5] The question is: if climate models differ by a factor of 2 to 3 in their climate sensitivity, how can they all simulate the global temperature record with a reasonable degree of accuracy. *Kerr* [2007] and S. E. Schwartz et al. (Quantifying climate change–too rosy a picture?, available at www.nature.com/reports/climatechange, 2007) recently pointed out the importance of understanding the answer to this question. Indeed, *Kerr* [2007] referred to the present work, and the current paper provides the ‘‘widely circulated analysis’’ referred to by *Kerr* [2007]. This report investigates the most probable explanation for such an agreement. It uses published results from a wide variety of model simulations to understand this apparent paradox between model climate responses for the 20th century, but diverse climate model sensitivity.

2. Method

[6] The application of simple climate models has elucidated the most important factors that, to first order, determine Earth's global mean surface temperature. A number of studies [*Raper et al.*, 2001; *Forest et al.*, 2002; *Knutti et al.*, 2002] have shown that there are three fundamental climate factors, namely: the climate forcing, the climate sensitivity and the efficiency of ocean heat uptake. Given these three factors one can calculate the evolution of the global mean surface temperature. All of the models applied to simulating the 20th century climate represent these factors in varying degrees of sophistication. The focus of the present work is on two of these factors: climate forcing and climate sensitivity. The role of the efficiency of ocean heat uptake will be discussed later. In the simpler energy balance models these three factors are specified, while in the more comprehensive three dimensional climate models the climate sensitivity and efficiency of ocean heat uptake are predicted.

[7] The climate forcing of the 20th century is calculated by assuming time evolving growth curves for greenhouse gas concentrations, aerosol concentrations and natural forcing factors that include solar variability and volcanic aerosols. It is important to note that the change in radiative flux is calculated and not prescribed in the fully coupled climate models. In the simpler energy balance models the actual radiative forcing is prescribed. The temporal evolution of the well-mixed greenhouse gases is more constrained by

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observations compared to changes in tropospheric aerosols [*Houghton et al.*, 2001]. Given the evolution of these forcing agents a temporal evolution of climate forcing is applied to the climate system, which then responds to the forcing. The magnitude of the surface temperature response for a given forcing is determined by the climate sensitivity. Uncertainties in climate forcing will be reflected in uncertainties in a models ability to replicate the observed climate record.

[8] The climate sensitivity is determined by a myriad of feedback processes in the climate system, which includes water vapor, clouds, sea ice and other processes. It is believed that much of the range in model climate sensitivity is due to uncertainties in cloud feedback processes [*Cess et al.*, 1996]. The reason for the 2 to 3 fold spread in climate sensitivity has been of great concern to the climate community [*Kerr*, 2004]. Although much focus has been on uncertainties in climate sensitivity, the question arises as to how important are uncertainties in forcing and the implications of these uncertainties in the ability to simulate the climate of the 20th century [*Hansen and Sato*, 2001].

[9] A large number of climate modeling groups have carried out simulations of the 20th century. These simulations employed a number of forcing agents in the simulations. Although there are established data for the time evolution of well-mixed greenhouse gases, there are no established standard datasets for ozone, aerosols or natural forcing factors. Results from nine fully coupled climate models [*Dai et al.*, 2001; *Boer et al.*, 2000; *Roeckner et al.*, 1999; *Haywood et al.*, 1997; *Mitchell et al.*, 1995; *Tett et al.*, 2002; *Meehl et al.*, 2004; *Meehl et al.*, 2000] and two energy balance models [*Crowley and Kim*, 1999; *Andronova and Schlesinger*, 2000] have been used to consider the relationship between total anthropogenic climate forcing and climate sensitivity. All of these simulations show very good agreement between the simulated anomaly in global mean surface temperature and the observational record. Many of these studies document the models equilibrium climate sensitivity and the aerosol and total forcing over the 20th century time period.

[10] The total climate forcings used in the present analysis were taken from the above cited references. When only total climate forcings were available from the studies, the total greenhouse forcing was used from *Houghton et al.* [2001] to back out the net aerosol forcing. Since the uncertainty in total greenhouse forcing (~20% or less) is much smaller than that due to aerosols, this approach introduces only small uncertainty in the present analysis.

3. Results

[11] The theoretical relationship between climate forcing and climate sensitivity is obtained by considering Earth's global energy budget [e.g., *Andreae et al.*, 2005],

$$\Delta \mathrm{Q} = \lambda \Delta \mathrm{T} + \mathrm{H}, \tag{1}$$

which states that the forcing of the climate system, ΔQ, is balanced by energy escaping to space, $\lambda\Delta T$, and energy stored in the oceans, H. Note that the total forcing of the system, ΔQ, is defined as the change in total radiative forcing between the end of the 20th century and the time period of the late 1800s. λ is the climate feedback parameter and is determined by the various feedback processes in the system. The climate sensitivity, ΔT_{2X}, is defined as the change in equilibrium global surface-air temperature due to a doubling of carbon dioxide, where at equilibrium, $H = 0$, and (1) implies,

$$\Delta \mathrm{Q}_{2\mathrm{X}} = \lambda \Delta \mathrm{T}_{2\mathrm{X}}. \tag{2}$$

Using (2), $\lambda = \Delta Q_{2X}/\Delta T_{2X}$, which means (1) can be written as,

$$\Delta \mathrm{Q} = (\Delta \mathrm{T}\ \Delta \mathrm{Q}_{2\mathrm{X}})/\Delta \mathrm{T}_{2\mathrm{X}} + \mathrm{H}. \tag{3}$$

The forcing due to a doubling of carbon dioxide is 3.7 Wm^{-2} [*Andreae et al.*, 2005], while the observed change in surface-air temperature is taken to be 0.6°C. The change in ocean energy storage is 0.7 Wm^{-2} [*Wigley*, 2005]. Substituting these values into (3) yields,

$$\Delta \mathrm{Q} = 2.22/\Delta \mathrm{T}_{2\mathrm{X}} + 0.7 \tag{4}$$

This expression indicates an inverse relationship between total forcing and climate sensitivity. With regards to the change in ocean heat storage, *Hansen et al.* [2005] estimate an uncertainty in H of $\pm 0.15\ \mathrm{Wm}^{-2}$. An analysis of coupled model simulations forced with a 1% per year increase in carbon dioxide indicates a spread in ocean energy storage, at the point of doubling, of 0.4 Wm^{-2}. Based on these estimate, the present analysis will assume an uncertainty of $\pm 0.2\ \mathrm{Wm}^{-2}$ in H.

[12] The model results for total anthropogenic forcing, ΔQ, and equilibrium climate sensitivity, ΔT_{2X}, are shown in Figure 1, while the solid line is based on (4), and the dashed lines above and below this central line arise from the $\pm 0.2\ \mathrm{Wm}^{-2}$ uncertainty in H. It is assumed that the natural forcing is much smaller than the anthropogenic forcing. These results clearly illustrate a strong inverse correlation between total anthropogenic forcing used for the 20th century and the model's climate sensitivity. Indicating that models with low climate sensitivity require a relatively higher total anthropogenic forcing than models with higher climate sensitivity.

[13] It may be argued that it would be more accurate to use a measure of the transient climate sensitivity in this analysis, since the simulation of the 20th century is a transient phenomenon. However, the transient climate response as defined as the change in global mean surface air temperature at the time of doubling in models assuming 1% per year increase in CO_2 show a similar range as the equilibrium sensitivity (1.4 to 3.8°C, see Table 9.1 by *Houghton et al.* [2001]). So whether equilibrium or transient sensitivity is used the results in Figure 1 will be unchanged.

[14] Note that the range in total anthropogenic forcing is slightly over a factor of 2, which is the same order as the uncertainty in climate sensitivity. These results explain to a large degree why models with such diverse climate sensitivities can all simulate the global anomaly in surface temperature. The magnitude of applied anthropogenic total forcing compensates for the model sensitivity.

[15] Although there is a clear inverse correlation between the forcing and the climate sensitivity there is some spread in the data points. Note that all the model results, except for one, fall close to or within the theoretical curves based on

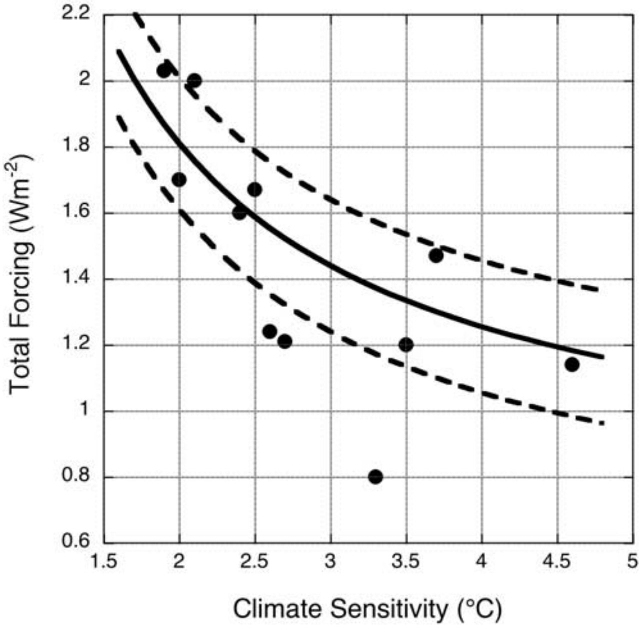

Figure 1. Total Anthropogenic Forcing (Wm^{-2}) versus equilibrium climate sensitivity (°C) from nine coupled climate models and two energy balance models that were used to simulate the climate of the 20th century. Solid line is theoretical relationship from equation (4). Dashed lines arise from assuming a ±0.2 Wm^{-2} uncertainty in ocean energy storage in equation (4).

the estimated uncertainty in H. This strongly suggests that the scatter among the models is mostly due to the range in modeled change in ocean heat storage.

[16] What is the major reason for the large uncertainty in total anthropogenic forcing? Figure 2 shows the correlation between total anthropogenic forcing and forcing due to tropospheric aerosols. There is a strong positive correlation between these two quantities with a near 3-fold range in the magnitude of aerosol forcing applied over the 20th century. This large uncertainty in aerosol forcing has recently been noted [*Anderson et al.*, 2003; *Schwartz*, 2004] as a significant challenge to the climate modeling community. Thus, the large uncertainty in aerosols over the past leads to a wide range in total anthropogenic forcing. Some of the models used in these simulations employed only the direct effect, while others used both direct and indirect effects of aerosols, which makes a more detailed comparison of simulated aerosol forcing difficult.

4. Conclusions

[17] These results indicate that the range of uncertainty in anthropogenic forcing of the past century is as large as the uncertainty in climate sensitivity and that much of forcing uncertainty is due to aerosols. In many models aerosol forcing is not applied as an external forcing, but is calculated as an integral component of the system. Many current models predict aerosol concentrations interactively within the climate model and this concentration is then used to predict the direct and indirect forcing effects on the climate system. Thus, it may be difficult to arrive at a standard approach that all models could employ for use in comparison of simulations forced in the same manner. However, a first step would be for models to employ standard emissions for aerosol gas precursors and particulate emissions.

[18] It is important to note that in spite of the threefold uncertainty in aerosol forcing, all of the models do predict a warming of the climate system over the later part of the 20th century. The warming is in essence bounded by the fact that climate sensitivity is a positive quantity and the total forcings used by modelers are also positive. This implies that the total forcing of the 20th century cannot be negative, i.e. the negative aerosol forcing cannot be larger than the positive greenhouse forcing, which bounds the magnitude of the total aerosol forcing.

[19] It could also be argued that these results do not invalidate the application of climate models to projecting future climate for, at least, two reasons. First, within the range of uncertainty in aerosol forcing models have been benchmarked against the 20th century as a way of establishing a reasonable initial state for future predictions. The analogy would be to weather forecasting where models assimilate information to constrain the present state for improved prediction purposes. Climate models are forced within a range of uncertainty and yield a reasonable present state, which improves the models predictive capabilities. Second, many of the emission scenarios for the next 50 to 100 years indicate a substantial increase in greenhouse gases with associated large increase in greenhouse forcing. Given that the lifetime of these gases is orders of magnitude larger than that of aerosols, future anthropogenic forcing is dominated by greenhouse gases. Thus, the relative uncertainty in aerosol forcing may be less important for projecting future climate change.

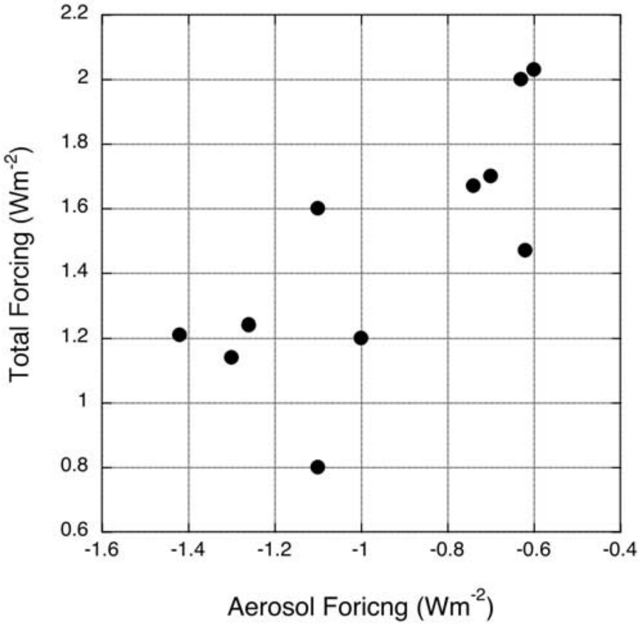

Figure 2. Total anthropogenic forcing (Wm^{-2}) versus aerosol forcing (Wm^{-2}) from nine fully coupled climate models and two energy balance models used to simulate the 20th century.

[20] Finally, the focus of this study has been on anthropogenic forcing. There is also a range of uncertainty in natural forcing factors such as solar irradiance and volcanic aerosol amount. It would of value to reduce uncertainties in these forcing factors as well. It would also be of great value to investigate the robustness of these results relative to the latest versions of coupled climate system models. However, given the fundamental physical relationship among climate response, climate forcing and sensitivity, i.e. (3), it is hard to imagine that these results do not apply to the latest coupled models.

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